Exchange airflows through doorways induced by door opening and occupant movement

Petri Kalliomäki
Exchange airflows through doorways induced by door opening and occupant movement

Petri Kalliomäki

A doctoral dissertation completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Engineering, at a public examination held on 10th of March 2021 at 12.00.
Remote connection link: https://aalto.zoom.us/j/68366659956

Aalto University
School of Engineering
Department of Mechanical Engineering
HVAC Technology
Supervising professor
Professor Risto Kosonen, Aalto University, Finland

Thesis advisor
Ph.D. Julian Wei-Tze Tang, University Hospitals of Leicester, UK

Preliminary examiners
Ph.D. Doc. Pertti Pasanen, University of Eastern Finland, Kuopio, Finland
Professor Jovan Pantelic, Katholieke Universiteit Leuven, Belgium

Opponents
Ph.D. Doc. Pertti Pasanen, University of Eastern Finland, Kuopio, Finland
Professor Manuel Gameiro da Silva, University of Coimbra, Portugal

Aalto University publication series
DOCTORAL DISSERTATIONS 21/2021

© 2021 Petri Kalliomäki

ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)

Images: Front cover: Saarinen, Pekka; Kalliomäki, Petri; Tang, Julian, Wei-Tze; and Koskela, Hannu. 2015. Large eddy simulation of air escape through a hospital isolation room single hinged doorway – Validation by using tracer gases and simulated smoke videos. Public Library of Science. PLOS ONE, 10(7): e0130667. doi:10.1371/journal.pone.0130667

Unigrafia Oy
Helsinki 2021

Finland
**Abstract**

In healthcare settings, patients with infectious airborne diseases are typically placed in negative pressure isolation rooms to reduce the spreading of the infections. Nevertheless, containment failures can still happen, and it has been assessed that the combined effect of door opening and occupants movement through the doorway can be among the most relevant factors causing the containment failures in hospital isolation rooms.

The aim of this thesis was to study the air volume exchange and airflow patterns across an isolation room doorway generated by door opening and occupant motion. The main focus of the study was on examining the differences between flows induced by hinged and sliding doors. The effects of several factors like door opening time (3-8 s), hold open time (2-25 s), passage (1 m/s) through the doorway, ventilation rate (0-12 ACH), pressure difference (0-20 Pa), temperature difference (0-3 °C) etc. on the exchange flows were investigated. The effect of directional airflow (net flow) was examined as a potential solution for reducing the contaminant escape through the doorway. Smoke visualizations, tracer gas measurements and CFD-simulations were used to examine the air volume exchange and airflow patterns across the doorway. All the experiments were carried out in a controlled laboratory environment consisting of a full-scale isolation room model. Occupant movement through the doorway was simulated with a moving manikin in the experiments.

The results show that the door opening generated a notable air volume exchange across the doorway (0.27-2.42 m³ depending on the examined case). Several factors affected the magnitude of these exchange flows, the clearest being the door type, door hold-open time, manikin passage, temperature difference and directional airflow. The sliding door opening was found to induce substantially smaller air exchange across the doorway compared to the hinged door. The reduction of the air volume migration with the sliding door varied between 36-79% compared to the hinged door induced exchange. The directional airflow across the doorway reduced the air volume migration substantially as well. The reduction was 38% and 60% with 90 L/s and 190 L/s directional airflow through the doorway respectively compared to reference case without notable directional airflow (only the hinged door type was tested). On the other hand, even a small temperature difference (2 °C) increased the air volume transfer notably, i.e. by 41% and 304% with the hinged and sliding doors respectively. Also, the manikin passage and door hold-open times were found to increase the exchange flows. Door opening time was not found to affect the air volume transfer notably.

The findings emphasize the effectiveness of sliding doors and the directional airflow in reducing the escape of contaminants through doorways induced by door operation. Even though utilization of sliding doors and directional airflows might not be directly feasible in old buildings, the installations should be at least considered when constructing new hospitals or remodeling the old.

**Keywords** door opening, occupant movement, airflow, contaminant dispersion, isolation room

<table>
<thead>
<tr>
<th>ISBN (printed)</th>
<th>978-952-64-0274-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISBN (pdf)</td>
<td>978-952-64-0275-8</td>
</tr>
<tr>
<td>ISSN (printed)</td>
<td>1799-4934</td>
</tr>
<tr>
<td>ISSN (pdf)</td>
<td>1799-4942</td>
</tr>
<tr>
<td>Location of publisher</td>
<td>Helsinki</td>
</tr>
<tr>
<td>Location of printing</td>
<td>Helsinki</td>
</tr>
<tr>
<td>Year</td>
<td>2021</td>
</tr>
</tbody>
</table>
Tekijä
Petri Kalliomäki

Väittöskirjan nimi
Oviaukon ilmavirtaukset oven aavuksen ja kulun seurauskona

Julkaisija
Insinööritieteiden korkeakoulu

Yksikkö
Kontekniikan laitos

Sarja
Aalto University publication series DOCTORAL DISSERTATIONS 21/2021

Tutkimusala
Energiatekniikka

Käsikirjoituksen pvm
17.12.2020

Väittöpaivä
10.03.2021

Väittelyluvan myöntämispäivä
03.02.2021

Kieli
Englanti

Monografia
Artikkeliväittöskirja

Esseeväittöskirja

Tiivistelmä

Tämän väittöskirjan tavoitteena on tutkia oven aavuksen ja oviaukosta kulkenemisen aiheuttamia virtauskuvoilta, rakenteita ja huoneesta toiseen kulkeutuvan ilman määриä. Keskeisenä tavoitteena oli tarkastella sarana- ja liuokuvien aiheuttamia ilmiöitä ja niiden eroja. Tavoitteena oli tarkastella myös muita virtauksiin vaikuttavia tekijöitä, kuten esimerkiksi oven aavasaukka (3-8 s), aukioloaikaa (2-25 s), kulku (1 m/s), ilmanvaihtoa (o-12 l/h), paine-eroa (o-20 Pa), lämpötilaaeroa (o-3 °C) jne. Lisäksi yhtenä tavoitteena oli tutkia tehostetun nettovirtauksen vaikutusta oviaukon kautta levävän ilmamäärian vähentämiseksi. Virtausilmiöitä tutkittiin savuvisualisoinnien, merkikkaasumittauksin ja CFD-simuloinnein, joiden avulla voitiin luoda yksityiskohtainen kuva eri tilanteista. Tutkimuksessa tehtiin suoritettiin laboratorioympäristöissä, johon oli rakennettu yksinkertainen sairaalan eristystilamalli. Ihmiskulku oviaukosta simuloitiin realistisen kokoisella mallinukella.

Tutkimuksen tulokset osoittivat, että oven aavuksen seurauskona oviaukon kautta kulkeutui huomattava määrä ilmaa huoneesta toiseen, (0,27-2,42 m3 riippuen tutkittavasta tilanteesta). Useat tekijät vaikuttivat virtauksiin, mutta merkittävimmät olivat: ovityyppi, oven aukioloaika, kulku oviaukosta, lämpötilaero ja tehostettu nettovirtaus. Mittauksien mukaan liukuvon aavuksen seurauskona oviaukon kautta kulkeutui levävän ilman määrää (36-79 %) verrattuna saranaoveneen tapaukseen. Myös tehostettu nettovirtaus oviaukon kautta pienensi huomattavasti oviaukon kautta karkaavan ilman määrää. Esimerkiksi 90 L/s ja 190 L/s ilmavirtaita oviaukon kautta (kohti eristystilaa) vähensivät kulkeutuvala levävän ilman määrää vastaavasti 38 % ja 60 % verrattuna tilanteeseen ilman tehostettua nettovirtausta. Toisaalta jok 2 °C lämpötilaero lisäsi ilman kulkeutumista oviaukon kautta huomattavasti, 41 % saranaoveneen tapauksessa ja 304 % liukuvon tapauksessa. Lisäksi kulku ja oven aukioloaika lisäävät karkaavan ilman määrää mutta oven aavusnopuudeella ei havaittu olevan suurta vaikutusta siihen.

Väittöskirjan tulokset korostavat liuokuvien ja tehostetun nettovirtauksen käyttöä oviaukojen virtausten hallinnassa. Menetelmiin sovelletaan vanhoissa sairaalarakennuksissa vai olla haastavaa, mutta ne voidaan ottaa huomioon suunniteltaessa uusia ja peruskorjatessa vanhoja rakennuksia.

Avainsanat
oven aavus, kulku, ilmavirta, epäpuhtauksien leviäminen, eristystila

ISBN (painettu)
978-952-64-0274-1

ISBN (pdf)
978-952-64-0275-8

ISSN (painettu)
1799-4934

ISSN (pdf)
1799-4942

Julkaisupaikka
Helsinkiläinen

Painopaikka
Helsinkiläinen

Vuosi
2021

Sivumäärä
159

urn
Acknowledgements

The research leading to this doctoral dissertation was started in the early 2010’s at the Finnish Institute of Occupational Health (FIOH). I joined FIOH indoor environment laboratory in Turku in 2012 and started working on A*Star-Tekes funded joint research project between FIOH and National University and University Hospital of Singapore. The work on this project opened a chance for me to explore and study exchange flows across isolation room doorways. Later, the interest towards this topic and to ventilation research in general led to the idea of pursuing a doctoral degree. This took shape when I started as a part-time doctoral student in the Department of Mechanical Engineering at the Aalto University School of Engineering in 2015 while still working full-time at FIOH. In 2016 the indoor environment laboratory moved from FIOH to Turku University of Applied Sciences (TUAS), where I have continued working on this research topic, among other things.

This whole journey, since joining FIOH in 2012 until today at TUAS, has been very interesting. To be fair, I’ve got to admit that combining work and part-time doctoral studies have not always been easy. However, I’ve been able work and study in creative and supportive environments under very competent guidance which have made it easier. Most of this mentoring has been provided by senior researcher Hannu Koskela from TUAS, who has been supervising the research projects that I’ve been involved at FIOH and TUAS. Hence, I would like to express my sincerest gratitude to Hannu. He’s support, guidance and advice related to this thesis journey and ventilation research in general has been priceless.

A special thanks goes also to my thesis advisor Ph.D. Julian Tang from University Hospitals of Leicester, UK, for the guidance throughout the thesis work. Thank you also for pushing me forward and for the swift replies to my queries concerning my thesis and research in general. Hopefully you have enjoyed your visits to Finland and our national delicacies like mämmi.

I would like to thank also my supervising Professor Risto Kosonen from Aalto University for the freedom and trust to let me carry out the thesis and studies independently. My co-authors also deserve acknowledgement. Special thanks go to Pekka Saarinen who made a great work with the CFD-simulations. Thank you also Kim Hagström, Ismo Grönvall and Harri Itkonen from Halton Oy. I want to also thank my colleagues at the built environment research group at TUAS. I’ve enjoyed the supportive and relaxed atmosphere that we have in our group.
I would also like to thank the Foundation LVY sr for financial support and the Finnish Society of Indoor Air Quality and Climate (FiSIAQ) and the Finnish Work Environment Fund for travel grants.

Most importantly I would like to thank and acknowledge my family. My mother, father and stepfather who have always supported me in my studies. My children, Julius, Aleksi, Hilla and Linda, you have brought a lot of joy to my life. And finally, I would like to thank my wife Helka. This would have not been possible without your neverending support. Thank you for standing by my side during this process.


Petri Kalliomäki
Contents

Acknowledgements ........................................................................................................... 1
List of Abbreviations and Symbols .................................................................................. 5
List of Publications .......................................................................................................... 6
Author’s Contribution ...................................................................................................... 7
1. Introduction .................................................................................................................. 9
  1.1 Background .............................................................................................................. 9
  1.2 Experimental studies on the exchange flows through doorways ..................... 10
  1.3 Numerical studies ................................................................................................. 12
  1.4 Objectives of the thesis ......................................................................................... 13
  1.5 The structure of the thesis .................................................................................... 14
  1.6 Novelty of the study .............................................................................................. 15
2. Methods ....................................................................................................................... 17
  2.1 Experimental methods .......................................................................................... 17
     2.1.1 The full-scale test chamber ............................................................................ 17
     2.1.2 Ventilation ....................................................................................................... 18
     2.1.3 Door and manikin movement cycles ............................................................... 20
     2.1.4 Smoke visualizations ....................................................................................... 21
     2.1.5 Tracer gas measurements ............................................................................... 21
  2.2 Numerical methods ................................................................................................ 25
  2.3 Summary of the methods ....................................................................................... 27
3. Results ......................................................................................................................... 29
  3.1 Airflow visualizations ............................................................................................ 29
     3.1.1 Baseline scenario without ventilation ............................................................... 29
     3.1.2 Visualizations with ventilation ....................................................................... 31
     3.1.3 Visualizations with directional airflow ........................................................... 34
  3.2 Tracer gas measurements ....................................................................................... 35
     3.2.1 Air volume transfer in the baseline scenario without ventilation ................ 36
     3.2.2 Air volume transfer with ventilation ............................................................... 38
     3.2.3 Air volume transfer with directional airflow ................................................... 41
# List of Abbreviations and Symbols

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACH</td>
<td>Air changes per hour</td>
</tr>
<tr>
<td>AIIR</td>
<td>Airborne infection isolation room</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational fluid dynamics</td>
</tr>
<tr>
<td>HCW</td>
<td>Healthcare worker</td>
</tr>
<tr>
<td>LES</td>
<td>Large eddy simulation</td>
</tr>
<tr>
<td>NPIR</td>
<td>Negative pressure isolation room</td>
</tr>
<tr>
<td>N2O</td>
<td>Nitrous oxide</td>
</tr>
<tr>
<td>OR</td>
<td>Operating room</td>
</tr>
<tr>
<td>PPE</td>
<td>Personal protective equipment</td>
</tr>
<tr>
<td>PPVL</td>
<td>Positive pressure ventilated lobby</td>
</tr>
<tr>
<td>RANS</td>
<td>Reynolds averaged Navier-Stokes -simulations</td>
</tr>
<tr>
<td>SF$_6$</td>
<td>Sulfur hexafluoride</td>
</tr>
<tr>
<td>STD</td>
<td>Standard error</td>
</tr>
</tbody>
</table>

- $X_{1\rightarrow2}$: Air volume migration from the room 1 (anteroom) to the room 2 (isolation room)
- $X_{2\rightarrow1}$: Air volume migration from the room 2 (isolation room) to the room 1 (anteroom)
List of Publications

This doctoral dissertation consists of a summary and of the following publications which are referred to in the text by their numerals.


II. Saarinen, Pekka; Kalliomäki, Petri; Tang, Julian, Wei-Tze; and Koskela, Hannu. 2015. Large eddy simulation of air escape through a hospital isolation room single hinged doorway – Validation by using tracer gases and simulated smoke videos. Public Library of Science. PLOS ONE, 10(7): e0130667. doi:10.1371/journal.pone.0130667.


Author’s Contribution

Publication I: Petri Kalliomäki planned the experiments together with the rest of the authors. Kalliomäki was responsible for carrying out the experiments. Kalliomäki had the primary responsibility of analyzing the data and writing the publication. Co-authors commented the manuscript during the writing and review process.

Publication II: Petri Kalliomäki carried out and analyzed the laboratory experiments. Kalliomäki also participated in analyzing the data and interpretation of the simulation results. Kalliomäki also participated in revising the publication manuscript. Pekka Saarinen had the primary responsibility of carrying out the simulations, analyzing the data and writing the publication.

Publication III: Petri Kalliomäki planned, carried out and analyzed the experimental parts of the publication. Kalliomäki participated in the planning of the simulations, and in analyzing and interpretation of the simulation results. Kalliomäki participated also in the writing of the parts concerning experimental measurements and in revising the publication manuscript. Pekka Saarinen had the primary responsibility to carry out the simulations, analyze the simulation data and writing the publication.

Publication IV: Petri Kalliomäki planned the experiments together with the rest of the authors. Kalliomäki was responsible for carrying out the experiments. Kalliomäki had the primary responsibility of analyzing the data and writing the publication. The co-authors commented the manuscript during the writing and review process.

Publication V: Petri Kalliomäki planned the experiments together with the rest of the authors. Kalliomäki was responsible for carrying out the experiments. Kalliomäki had the primary responsibility of analyzing the data and writing the publication. The co-authors commented the manuscript during the writing and review process.
1. Introduction

1.1 Background

Negative pressure isolation rooms (NPIRs) are now extensively used in hospitals, worldwide, following the severe acute respiratory syndrome (SARS-CoV) outbreaks of 2003 and the subsequent worries about avian A/H5N1, pandemic A/H1N1pdm09 influenza, Middle East Respiratory Syndrome-associated coronavirus (MERS-CoV), and most lately pandemic SARS-CoV-2 virus. The trend seems to be that these sorts of zoonotic epidemics/pandemics will appear at an accelerating pace in the future and are often severely affected by anthropogenic effects like increasing travel, population, urbanization, contacts between humans and wild animals etc. (Naicker, 2011, Smith et al., 2014, Gibb et al., 2020). Due to increased usage and future demand isolation rooms have been under intense research and scrutiny lately (Rice et al., 2001; Saravia et al., 2007; Hyttiläinen et al., 2011).

In healthcare settings, patients with infectious airborne diseases are typically placed in NPIRs to prevent the spreading of pathogens and hence to reduce the risk of cross-infection and nosocomial infections. Expiratory activities, like breathing, talking, coughing and sneezing, release substantial number of droplets of different sizes (Papineni and Rosenthal, 1997; Morawska et al., 2009; Xie et al., 2009). Released droplets go through evaporation in the air to become droplet nuclei (Wells, 1934). After the evaporation, the droplet nuclei (diameter \(<10 \, \mu m\)) can stay suspended in the air for extended periods, be dispersed by ventilation and room airflows and hence contribute to disease transmission over long distances (Xie et al., 2007). On the other hand, small droplets (\(\leq 60 \, \mu m\)) and large droplets (\(>60 \, \mu m\)) deposit more rapidly onto nearby surfaces because gravity is dominating their movements over e.g. ventilation induced effects. Hence droplets contribute only to short range transmission of diseases.

To prevent exposure to airborne infectious agents, hospital staff and visitors wear personal protective equipment (PPE) while visiting isolation rooms. Additionally, negative pressure and sufficiently high ventilation rates (6-12 air changes per hour, ACH) are recommended for isolation rooms (e.g. ASHRAE 170-2017; CDC, 2005; HTM 03-01 Part A, 2007; WHO, 2014) to limit the spreading and to reduce the exposure to airborne pathogens. Nevertheless, containment failures can still happen (Pavelchak et al., 2000; Tang et al., 2006). There are several reasons for this: the opening of the isolation room doors, which can lead to transient breakdown of negative pressure isolation conditions (Tang et al., 2005); movement through the doorway (e.g. staff, visitors), as air
and airborne contaminants can be dragged out of the isolation room in the wake of a moving person; the opening of the windows etc. In fact, it has been assessed that the combined effect of the door opening and occupant movement through the doorway can be among the most relevant factors causing containment failures in hospital isolation rooms (Pavelchak et al., 2000; Tang et al., 2006). Indeed, a study by Tang et al. (2005) has described a case where the operation of an isolation room door has probably caused a containment failure, exposure to varicella-zoster virus and subsequent infection of a healthcare worker (HCW) resulting in chickenpox.

1.2 Experimental studies on the exchange flows through doorways

In general, exchange flows through doorways have been studied for quite some time already. Historically the focus has been on the steady state airflows through large rectangular openings in vertical and horizontal partitions (e.g. van der Maas (Ed.), 1992; Etheridge and Sandberg, 1996; and references therein). Although the focus has been on residential and industrial environments, other specific environments, like hospitals, have also been investigated (Baird and Whyte, 1969; Shaw, 1976; Lidwell, 1977). Additionally, many studies have investigated the containment effectiveness of the isolation rooms by monitoring the pressure difference of the rooms while the doors are closed (Fraser et al., 1993; Rice et al., 2001; Saravia et al., 2007). However, effects caused by dynamic events such as the door opening and occupant motion on the exchange flows through doorways has previously (before 21st century) received only limited attention (Shaw, 1976; Kiel and Wilson, 1989; Hayden et al., 1998).

Recently, more attention has been given to the door opening and occupant movement (through the doorway) generated transient breakdown of isolation conditions and contaminant transport out of the isolation rooms. For example, Rydock and Eian (2004) examined a tracer gas migration out of isolation rooms with a person exiting an isolation room and found elevated tracer gas concentrations in the anteroom and corridor. Adams et al. (2011) used fluorescent microspheres (particles) to investigate the effect of pressure differential on the containment effectiveness of isolation rooms. They found that increasing pressure differentials reduced the door opening and care provider movement induced contaminant transfer across the doorway. Kokkonen et al. (2014) carried out performance testing of airborne infection isolation rooms (AIIRs) by tracer gas techniques in real hospital settings. They found that up to 1.7 m$^3$ of air can migrate to an anteroom during door opening and movement of a HCW through the doorway. Chang et al. (2016) carried out tracer gas measurements to study the contaminant inleakage produced by a hinged door opening and human walking into a control room of a nuclear power plant. They found inleakage volume up to 1.0 m$^3$ and that there was a linear increase in inleakage volume with increasing door swing time. However, they concluded that the increase was mainly caused by the enhanced effect of the human movement induced airflows
as the door pumping volume showed only little variation as a function of swing time.

In addition to full-scale studies (like the ones mentioned above), door opening motion induced effects on doorway exchange flows have been studied with small-scale models as well (Kiel and Wilson, 1989; Tang et al., 2005; Eames et al., 2009; Tang et al., 2013; Fontana and Quintino, 2014; Hathway et al., 2015, Papakonstantis et al., 2018). These experiments have demonstrated the usability of small-scale models in studying the door opening generated air exchange flows across the doorways.

Common nominator to many small-scale models is that they are carried out without ventilation and occupant motion. However, those factors play an important role in the airborne contaminant dispersal in indoor environments and also in exchange flows through doorways. For instance, a negative pressure (generated by a supply-exhaust flow rate differential) is typically used to produce a directional airflow towards isolation rooms when doors are closed. With a high enough supply-exhaust flow rate differential, the directional airflow may be sustained also across an open doorway. Although high directional airflows can be disturbed by the door opening motion, occupant movement, temperature difference, turbulence etc., they may still substantially reduce the air volume exchange and hence also the airborne contaminant dispersion through the doorway (Shaw, 1976; Hayden et al., 1998; Shao et al., 2020). Nevertheless, optimal airflow rates through doorways to control cross-contamination are still unknown and additional studies taking into account the effects of dynamic events (such as the door opening and occupant movement) when applying directional airflow are needed.

Occupant movement is also known to affect the indoor air flows and contaminant spreading in closed environments (Okamoto and Sunabashiri, 1992; Bjørn et al., 1997; Matsumoto and Ohba, 2004; Poussou and Plesniak, 2012, 2015; Wu and Lin, 2015; Tao et al., 2018; Bhattacharya et al., 2020 A). Human movement creates a dynamic and complex mixing process and flow field behind the moving body which may substantially enhance pollutant dispersion and transport (Han et al., 2015). Especially, contaminants can be dragged in the wake of a moving body and hence contribute to transport of pollutants over long distances. Recently it was estimated that human movement can generate a wake flow, which can sustain airstreams up to 10 s in the walking direction (Bhattacharya et al., 2020 A).

Studies investigating the effect of occupant movement in conjunction with a door opening are much more limited. However, it has been shown that the occupant movement can contribute notably to contaminant transmission through the doorway between adjacent zones (Shaw, 1976; Hayden et al., 1998; Tang et al., 2013; Chang et al., 2016; Shao et al., 2020). For instance, Shaw (1976) estimated the amount of air that a fast and slowly walking person transfers through a doorway. He found that when a person walked fast across the doorway, the transferred air volume was about 0.286 m$^3$ and that when the person walked slowly, the air volume transfer was about 0.0875 m$^3$ (unfortunately there was no information what the walking speeds were). Interestingly, Hayden et al.
(1998) found that the effect of entry/exit on the air volume migration through a doorway was the dominant factor only with a sliding door.

Another important factor affecting the exchange flows through doorways is temperature difference. The effect of temperature difference on the heat and mass transfer through rectangular openings in static conditions have been studied extensively (Brown and Solvason, 1962; Liddwell, 1977; van der Maas (Ed.), 1992; Etheridge and Sandberg, 1996; and references therein). However, there are notably fewer studies examining the effects of the door pumping and human movement on the temperature difference driven airflows through doorways (Shaw, 1976; Kiel and Wilson, 1989). Although the door pumping effect may delay the onset of the temperature driven flow, the effect of temperature difference on the exchange flows is significant, especially with large temperature differences and long door opening times.

Like discussed above, the exchange flows through doorways have been studied widely and many factors affect them greatly (e.g. door type, occupants movement, ventilation, temperature difference). Nonetheless, many of the studies investigating the factors affecting the doorway exchange flows have focused exclusively on the hinged door generated airflows. Only a few studies have systematically examined the differences between hinged and sliding doors (Shaw, 1976; Hayden et al., 1998; Tang et al., 2013) and even fewer through full-scale experiments (Shaw, 1976; Hayden et al., 1998) although the differences between the flows of the two door types are not clear. For example, some of the studies have shown that the usage of sliding doors can reduce the airflow out of the isolation rooms compared to hinged doors (Shaw, 1976). However, it has also been argued that there is no substantial difference on the air volume exchange induced by the two door types when occupant movement through the doorway has been taken into account (Hayden et al., 1998). Clearly, further evidence is needed to clarify the differences between the sliding and hinged door opening induced flows. Additionally, by knowing the optimal door type and related parameter values for the door opening we might be able to notably reduce the exchange flows through doorways and hence also the transport and the possible exposure to airborne contaminants in adjacent rooms and spaces.

1.3 Numerical studies

Computational fluid dynamics (CFD) is a computer based numerical method which has established itself as a popular, useful, and powerful research method in room air distribution science (Chen, 2009; Li and Nielsen, 2011; Nielsen, 2015). In CFD the governing equations of fluid flow (like airflow) are numerically solved, so that the fluid movements and related phenomena can be investigated. CFD have been used in the room air distribution research for over 50 years and has been applied to a wide variety of different cases (Nielsen, 2015). Nevertheless, methods for modeling indoor air flows have advanced notably in recent years.

Historically, steady state simulations solving Reynolds averaged Navier-Stokes (RANS) equations have been mostly used in indoor airflow studies due
to their efficiency and low computational cost. On the other hand, unsteady RANS have been typically used if transient effects must have been simulated. However, recently also Large Eddy Simulations (LES) have become feasible, thanks to proliferation in computing power.

Verification and validation of the simulations play a key role in the quality of the CFD simulation results. That is, the accuracy of the models depends on the applied simulation methods (e.g. turbulence models, discretization schemes) and the validity of the given boundary conditions. It has been pointed out by several researchers that it is important to validate the models prior to extensive use of them (Roache, 1997, 1998; Li and Nielsen, 2011). On the other hand, well defined and properly performed simulations can save effort, time and money of costly and complex experiments.

CFD simulations have been widely applied to hospital ventilation, particularly to modelling of operating and isolation room air flows (e.g. Huang and Tsao, 2005; Noakes et al., 2006; Shih et al., 2007; Richmond-Bryant, 2009; Liu et al., 2009; Villafuertela et al., 2013; Romano et al., 2015; Sadrizadeh, 2016; Wang et al., 2018). For example, Shih et al. (2007) modelled dynamic airflow within an isolation room and concluded that “the opening and closing of a sliding door has a profound effects on internal pressure and velocity distributions.” Later e.g. Villafuertela et al. (2013) used CFD to assess the potential of ventilation systems to reduce the risk of exposure to patient released contaminants in isolation rooms. Whereas Sadrizadeh (2016) and Wang et al. (2018) have used CFD to compare different (old and novel) ventilation designs for hospital operating room (OR) environments, just to point out a few studies.

Development of computing power and advances in simulation methods of moving objects with time-accurate LES have made it compelling to apply these new techniques to practical problems such as the door and human motion induced flows. For example, Choi and Edwards (2008) have simulated a manikin walking through an open doorway (in the absence of door and ventilation). In a follow up study, Choi and Edwards (2012) modelled the manikin walking from a dirty area to a clean area through a vestibule fitted with either hinged or sliding doors. The visualizations and results provided by the simulations (Choi and Edwards, 2008; 2012) are very detailed and show that LES can offer a more accurate method compared to RANS for studying the door and moving object induced flows.

1.4 Objectives of the thesis

The overall objective of this thesis was to study the air volume exchange and airflow patterns across an isolation room doorway generated by transient effects of door opening and occupant motion. The general objective can be further developed into main research questions:

1. How much air is transported through the doorway and what kind of airflow patterns are induced by the door opening? (Publications I-V).
2. How much the air exchange through the doorway can be reduced by optimal choice of door opening parameters? (Publication I).
3. What is the effect of occupant movement through the doorway on the exchange flows? (Publications I-V).
4. What are the differences between the exchange airflows generated by a hinged and sliding door motions? (Publications I and IV).
5. How effective is directional air flow (net flow) in reducing the door opening and occupant movement induced air exchange? (Publication V).

The objectives were investigated systematically by utilizing qualitative and quantitative experimental and modelling methods illustrating, measuring and simulating the air volume exchange and the airflow patterns across the doorway.

1.5 The structure of the thesis

This thesis consists of five publications (I-V), each focusing on different topics regarding the door opening induced exchange flows. Publications I-III deal with baseline test cases carried out in a quiescent environment without ventilation. Publication IV deals with more complex scenarios with ventilation and Publication V with directional airflows. This way the objectives are covered in various environmental conditions as summarized below and in Figure 1.

In Publication I, the objective was to characterize the hinged and sliding door induced exchange flows through doorways without ventilation applied. In this baseline study, the airflows through the doorway generated by the door opening and occupant movement were examined experimentally in a full-scale laboratory environment. The focus was on investigating systematically and comprehensively the effects of various parameters, like different door opening, hold-open, and total cycle times, opening sizes, temperature difference, and occupant movement. The publication contributed especially on characterizing the baseline flow phenomena in a quiescent environment.

CFD simulations were used to further examine the baseline flow phenomena across the doorway in Publications II and III. The objective of the publications was to produce a time accurate CFD model of the door opening scenarios (for both door types) through which the flow phenomena could be studied in more detail. LES-simulations were carried out for this purpose. As the publications concentrated only on one door type per publication (Publication II to the hinged door and Publication III to the sliding door), they offered a possibility to focus on the hinged and sliding door induced flows individually and to characterize them more comprehensively.

Publication IV extended the scope of the study to cases with more realistic environmental parameters (i.e. with ventilation applied). The objective of the publication was to investigate experimentally the effect of typically utilized ventilation rates, a supply-exhaust flow rate differential (creating a pressure difference between the rooms) and occupant movement on the air volume exchange and
the airflow patterns through the isolation room doorway induced by the opening of the hinged and sliding doors.

Publication V was built on the findings and results of Publications I-IV and studied a potential method (enhanced directional airflow) for reducing the air exchange. The enhanced directional airflow method was based on the idea of generating an elevated net flow through the doorway towards the isolation room by producing momentary excess supply to the anteroom and excess exhaust from the isolation room during the door operation. The main objective of Publication V was to examine the effectiveness of the method in reducing the air volume exchange through a doorway generated by a hinged door opening, temperature difference and occupant movement.

1.6 Novelty of the study

As discussed previously, the exchange flows across doorways in steady state conditions have been examined widely. However, there seems to be a clear lack of research considering the transient effects of the door opening motion (pumping) and occupant movement (passage) related to exchange flows through doorways. This thesis will provide detailed and novel information on this topic. Especially, there is an evident lack of profound and comprehensive analysis between the hinged and sliding door induced exchange flows under various operating conditions. More studies investigating the range of door opening induced flows are needed to clarify the differences between sliding and hinged doors.

For example, the effect of door opening, hold-open, and total cycle times, opening sizes, temperature difference, and occupant movement on the doorway exchange flows are characterized in Publication I. No such comprehensive testing and comparison of the effect of different door opening parameters on the exchange flows for hinged and sliding doors have been previously reported.

The CFD simulations (in Publications II and III) offer a novel and detailed information on the temporal evolution of the flow patterns and air volume migration across the doorway induced by the hinged and sliding door motion combined with the effect of manikin movement.
Additionally, it is not clear what is the effect of ventilation rates on the airborne contaminant transfer across the doorway, with respect to the door opening motion and human movement induced flows (Lidwell, 1977). Publication IV provides clarity and novel information on this topic by characterizing the doorway exchange flows induced by door opening and occupant movement with different isolation room ventilation rates.

In Publication V, the effect of enhanced directional airflow (net flow) on the exchange flows through doorways induced by door opening motion and occupant movement was examined. Previous research on this topic has focused on steady state conditions or on low airflow rates across the doorway in dynamic scenarios with the door opening. This study extends the scope to higher net flow rates and hence provides new information about the effectiveness of the directional airflow method in realistic isolation room environments.
2. Methods

In this section both the experimental and the numerical methods are described. Although the main focus of this thesis was on the experimental investigations, also complementary CFD simulations were carried out for visualization and better understanding of the transport phenomena. General description of the CFD methods will be provided in this chapter.

2.1 Experimental methods

2.1.1 The full-scale test chamber

All the experiments in this thesis were carried out in a controlled laboratory environment. A mock-up simulating a simplified hospital isolation room was built into the laboratory. The mock-up was constructed out of cleanroom elements isolating it from the larger laboratory space.

In Publications I-IV the experiments were carried out in a mock-up consisting of two identical rooms (rooms 1 and 2) separated by a dividing wall with a connecting door in the middle. The room 1 was named as the anteroom and the room 2 as the isolation room. The naming convention was based on the opening direction of the door (it typically opens into the isolation room). The rooms were 4.7 m wide, 4.0 m long and 3.0 m high, see Figure 2 for further details of the layout. The rooms were identical, which enabled investigation of the exchange flows in both directions across the doorway simultaneously.

In Publication V the isolation room was slightly lower in height (2.6 m high) and the anteroom smaller altogether (2.4 m wide, 2.4 m long, and 2.45 m high) compared to Publications I-IV. Hence, the whole system resembled more a typical hospital isolation room setting, see Figure 3 for details of the layout.

In all experiments, the occupant movement through the doorway was simulated with a mechanical movement of a manikin. The manikin was 1.7 m tall, 0.4 m wide (on the shoulder level) and it was made out of foamed plastic. The manikin was fixed to a small cart (on wheels) moving along a rail, which ran embedded to the floor between the two rooms (see Figure 4). The movement of the manikin is described more accurately in section 2.1.3.

In Publications I and IV two different door types were examined experimentally, i.e. single leaf hinged and sliding doors. In both cases, the doorway was 2.06 m high and 1.10 m wide and the door was opened by an automated door
Methods

opener. The door was chosen to be sufficiently wide so that it would correspond to the requirements at hospitals (access to rooms with wheelchairs and patient beds). In Publication V, the effect of directional airflow on door opening induced exchange flows was studied only with the hinged door.

2.1.2 Ventilation

The experiments in Publication I were carried out without ventilation as it was focusing on baseline cases in a quiescent environment. However, the effects of ventilation were examined in Publications IV and V. Typical overhead mixing ventilation with 94 L/s and 188 L/s flow rates (corresponding to 6 and 12 air changes per hour (ACH) respectively) was used in the anteroom and in the isolation room in the experiments in Publication IV. Conical diffusers with radial jet along the ceiling were used as supply air terminals. The section of the diffuser supplying air towards the doorway was blocked. Exhaust grilles were used to extract the air from the rooms. The locations of the supply air terminals and exhaust grilles are shown in Figure 2. The supply air temperature and heat loads were set so that 22 °C room temperature was obtained. In cases where the effect...
of temperature difference was studied, one of the rooms was heated with con-vectors.

Publication V focused on examining the effect of enhanced directional airflow (increased net flow) of 90 L/s and 190 L/s through the doorway on the door opening and occupant movement generated air volume exchange and airflow patterns between the rooms. The increased net flow through the doorway towards the isolation room was created by producing excess supply to the anteroom and excess exhaust from the isolation room during a door opening. This was realized in the experiments by manually adjusting dampers in the supply and exhaust ducts. That is, the supply air of the isolation room was directed to the anteroom and the anteroom exhaust to the isolation room when the door between the rooms started to open. After the door had closed again, the dampers were returned to the original positions. Only readily available flow rates were used so that the system was able to react rapidly to damper changes when door started to open or close. It was considered that adjusting the flow rates by changing the fan speed would have resulted in a slow response due to a ramp up time of the fans (and hence it would have been challenging for the system to react to the relatively short duration of the door opening).

Mixing ventilation was also used in the anteroom and in the isolation room in Publication V. However, in this case, the supply air was distributed through multi-nozzle diffusers installed in the ceiling in the middle of the rooms and extracted through exhaust grilles. The nozzles of the supply diffusers were directed away from the door and from the exhausts to avoid supply air short circuiting and producing unwanted air transfer through the doorway during the door opening. The details of the supply and exhaust terminal locations are presented in Figure 3.

In the reference case (without enhanced directional airflow in Publication V), the anteroom supply and exhaust flow rates were both set to 50 L/s. In the isolation room the supply and exhaust flow rates were set to 170 L/s and 200 L/s respectively. The (supply) flow rates corresponded to 12 ACH in both rooms, which is typically recommended value for new isolation rooms (e.g. ANSI/ASHRAE/ASHE Standard 170-2017). The supply air temperature and

Figure 4. The manikin simulating the human movement through the doorway (Publication I).
heat loads in the isolation room and in the anteroom were set so that 21.5 °C room temperature was obtained (in both rooms). In cases where the effect of temperature difference was studied, isolation room was heated with convectors.

The supply and exhaust flow rates and the pressure difference (between the isolation room and anteroom) were measured with a micromanometer (Swema 3000, Swema, Sweden) in all experiments. Calibrated orifices were installed to the supply and exhaust ducts for accurate airflow rate measurement. The accuracy for airflow rate measurement was ±4 L/s and for pressure ±0.3 Pa. The supply, exhaust and room air temperatures were monitored with thermistors (Craftemp, Sweden, ±0.2 °C accuracy, 1 min sampling frequency).

### 2.1.3 Door and manikin movement cycles

Schematics of the hinged door and manikin movement cycles are shown in Figure 5. The cycle was essentially similar for the hinged and sliding door cases. Prior to each movement cycle, the manikin stood in the middle of a room. In the beginning of the cycle, the manikin accelerated quickly into the full speed of 1 m/s. The speed was considered as representative movement pace of the adults on population level (Bohannon, 2008) although young adults tend to walk faster (Bohannon and Andrews, 2011). After acceleration the manikin advanced towards the door and stopped in front of it. Shortly after the manikin had stopped in front of the door, the door started to open. After the door had opened fully, the manikin started moving again and proceeded into the other room through the doorway. On the other side of the doorway, the manikin stopped at the center of the room and after a short wait the door started to close behind the manikin. After the door had closed the movement cycle was considered to be over.

In the cases when only the door opening motion induced effects were investigated, the movement cycle was similar as described above but without manikin movements.

In Publication I several different door opening, hold-open and total cycle times were studied. In the other publications (II-V) the door opened in 3 s, stayed fully open for 8 s and closed in 5.4 s. The opening and closing times were relatively short but they still complied with the requirements of EN 16005 standard. Long

![Figure 5](image_url). Illustration of the door opening and passage movement cycles for the hinged door (the cycles were essentially similar for the sliding door) (Publication IV).
enough hold-open time ensured that the manikin could safely pass through the doorway without colliding with the door. Additionally, the manikin had to stop sufficiently far away from the hinged door on the isolation room side to avoid collision with the opening door. Otherwise, the movement cycles were similar with both door types. The movements of the manikin and the doors were controlled by a computer program, making the synchronization of the door and the manikin movements easier and accurately repeatable throughout the experiments.

2.1.4 Smoke visualizations

Visualizations of the airflow patterns induced by the door opening motion and the manikin movement were important part of the study. The smoke visualizations were carried out to qualitatively illustrate the airflow patterns and to compare differences between sliding and hinged door opening generated flows. The smoke used in the experiments was produced with a smoke machine and according to manufacturer, the average particle size of the generated smoke was $1-1.5 \, \mu m$ (Product information document, https://www.martin.com/en/site_elements/martin-hints_and_tips-particle-size-fluid-density-and-refractive-index-values, accessed 5.11.2020). The settling of such fine particles due to gravity is slow and hence the smoke was capable of following the air flows realistically, making it suitable for airflow visualizations.

In the experiments, the smoke was released into one of the rooms at a time, so that the whole room was filled with smoke. In the other room (initially empty of smoke), on the other side of the doorway, lights were used to illuminate a plane (horizontal or vertical depending on the examined plane) in which the air movements were planned to be examined. In the experiments, the lights and camera were placed as far away from the doorway as possible in order to minimize the interference with the doorway flows. The smoke flow through the doorway was recorded with a digital SLR (single lens reflex) camera. Only still images extracted from the recorded videos are shown in this thesis.

2.1.5 Tracer gas measurements

Tracer gas measurements were performed to measure the total volume of the air flowing through the doorway generated by the door opening and manikin movement. Tracer gases are gaseous substances which can be used to tag air and hence to trace its bulk movements. Tracer gases have been used long and widely in building ventilation research (see e.g. Sherman, 1990; Etheridge and Sandberg, 1996; and references therein). Tracer gases have also been found to be suitable for simulating the dispersion of airborne contaminants and droplet nuclei (possibly carrying airborne infections) realistically indoors (Bivolarova et al., 2017; Kierat et al., 2018; Ai et al., 2020).
Baseline scenario

Two tracer gases (i.e. sulfur hexafluoride (SF₆) and nitrous oxide (N₂O)) were used in the baseline scenario experiments without ventilation (mainly in Publication I, but also in the experimental parts in Publications II and III). Utilization of two tracer gases at the same time allowed the tracer exchange to be measured in both directions through the doorway simultaneously. In the beginning of each experimental case, the gases were dosed into different rooms. The gases were diluted with air before the release into the separate rooms. After the release, the tracers were mixed in the rooms with fans. The fans were switched off one minute before each door opening. A photoacoustic multi-gas analyzer (Bruel&Kjaer model 1302) was used to measure the tracer concentrations. The concentrations were measured in three different locations: in the anteroom (room 1), in the isolation room (room 2) and in the surrounding laboratory. Perforated plastic tubes were used for sampling. The tubes enabled uniform sampling and reduced the possible effect of concentration gradients. The samples were taken serially, with 90 s intervals between each room.

All test cases consisted of 5-12 door openings (depending on the case). Each opening was separated by 45 minutes. After all openings were carried out for each case, the rooms were flushed with fresh air to remove the residual tracers before a new measurement with different set of parameter values started. The measurements were carried out similarly for the hinged and sliding doors.

The tracer gas measurement analysis was based on the assumption that the test chamber formed a closed system. This assumption was considered valid as there were no ventilation in the rooms in the baseline experiments and the test chamber was made of sealed cleanroom elements. Mass conservation of the tracer gases yields:

\[
\begin{align*}
\Delta m_{SF_6,1} &= m_{SF_6,2\rightarrow1} - m_{SF_6,1\rightarrow2} \\
\Delta m_{N_2O,2} &= m_{N_2O,1\rightarrow2} - m_{N_2O,2\rightarrow1},
\end{align*}
\]

where \(\Delta m_{SF_6,1}\) and \(\Delta m_{N_2O,2}\) are the SF₆ and N₂O mass changes in the rooms 1 and 2 respectively, \(m_{SF_6,2\rightarrow1}\) and \(m_{SF_6,1\rightarrow2}\) are the SF₆ masses migrating from the room 2 to the room 1 and from the room 1 to the room 2 respectively and \(m_{N_2O,1\rightarrow2}\) and \(m_{N_2O,2\rightarrow1}\) are the N₂O masses migrating from the room 2 to the room 1 and from the room 1 to the room 2 respectively. Equation (1) can be expressed with volume concentrations:

\[
\begin{align*}
\Delta c_{SF_6,1} V_1 &= c_{SF_6,2} X_{2\rightarrow1} - c_{SF_6,1} X_{1\rightarrow2} \\
\Delta c_{N_2O,2} V_2 &= c_{N_2O,1} X_{1\rightarrow2} - c_{N_2O,2} V_{2\rightarrow1},
\end{align*}
\]

where \(\Delta c_{SF_6,1}\) and \(\Delta c_{N_2O,2}\) are the SF₆ and N₂O tracer concentration changes in the rooms 1 and 2 respectively, \(V_1\) and \(V_2\) are the volumes of the rooms 1 and 2 respectively, \(c_{SF_6,1}\) and \(c_{SF_6,2}\) are the SF₆ tracer concentrations (prior to a door opening) in the rooms 1 and 2 respectively, \(c_{N_2O,1}\) and \(c_{N_2O,2}\) are the N₂O tracer concentrations (prior to a door opening) in the rooms 1 and 2 respectively, and \(X_{1\rightarrow2}\) and \(X_{2\rightarrow1}\) are the air volumes migrating from the room 1 to the room 2 and
from the room 2 to the room 1 respectively. Solving for the migrating air volumes gives:

\[
\begin{align*}
X_{1\rightarrow2} &= \frac{c_{SF_6,2}\Delta c_{N_2,2}V_2 + c_{N_2,2}\Delta c_{SF_6,1}V_1}{c_{N_2,1}c_{SF_6,2} - c_{N_2,2}c_{SF_6,1}} \\
X_{2\rightarrow1} &= \frac{c_{SF_6,1}\Delta c_{N_2,0,2}V_2 + c_{N_2,0,1}\Delta c_{SF_6,1}V_1}{c_{N_2,0,1}c_{SF_6,2} - c_{N_2,2}c_{SF_6,1}}
\end{align*}
\]

Equation (3) shows that the rooms can have any initial concentration of the tracers before the door opening (as long as the concentrations are not the same on both sides of the doorway) due to which various door openings can be performed without flushing the rooms between the openings.

In practice the model rooms were not fully airtight. For instance, a small amount of air was removed from the system as a result of the sampling. Nevertheless, this process was found to be slow and hence to have a negligible effect on the results.

In Publication I (i.e. in this baseline scenario) several different door opening, hold-open, and total cycle times were studied with tracer gas measurements. Also, the door opening angle, effect of the manikin movement, its direction and 2 °C temperature difference on the air volume exchange between the rooms were investigated. All the experiments were carried out for the hinged and sliding doors for comprehensive comparison of the differences.

**Scenarios with ventilation**

The air volume transfer across the doorway was also studied when ventilation was in use (in Publications IV and V). Similarly, as in the baseline experiments in Publication I, two tracer gases, SF₆ and N₂O, were used in the experiments carried out in Publication IV. Again, this made it possible to measure the air volume exchange across the doorway in both directions at once. However, only one tracer gas was utilized when the effect of directional airflow was studied (in Publication V), which allowed the air volume transfer measurement only to one direction through the doorway, namely from the isolation room to the anteroom. Otherwise the tracer gas methods were essentially similar in both Publications (IV and V).

In the experiments with ventilation the tracer gases were supplied continuously to the supply air ducts through which they dispersed into the rooms. Mixing ventilation was assumed to provide quick dispersion and uniform distribution of the gases inside the rooms. Two gas analysers (Brüel&Kjær model 1302), each dedicated to a specific tracer, were used to measure the tracer gas concentrations directly from the exhaust ducts of the different rooms. After the release of the tracer gases was started, it was waited until steady state concentrations were achieved in both rooms. After the tracer concentrations had achieved steady state in their separate rooms, first door opening was carried out. Before the door opening the analysers were changed to monitor the tracer concentrations in the empty rooms (i.e. tracer free before the door opening). The door opening induced the tracer gases to flow across the open doorway and hence led
to an abrupt increase in their concentrations in the opposite rooms. The tracer migration came to a stop when the door closed, and subsequently the concentrations started to decline towards the initial background values before the door opening. The declining concentrations were monitored for an hour to ensure that they had reached initial background values before the next door opening. Prior to each door opening the tracer concentrations (on their supply rooms) were checked to ensure that they had remained in the steady state level. A sampling interval of ~40 s enabled adequate monitoring of the concentration changes within the rooms.

The tracer gas measurement analysis was based on the assumption that the tracer gases were able to leave the test chambers only through the exhausts, i.e. there were no leakages to the surrounding environment. This was regarded as a credible assumption as the test chamber was in negative pressure related to the adjacent spaces and because it was made of sealed cleanroom elements.

The air volume transfer through the doorway from the isolation room (room 2) to the anteroom (room 1) was calculated based on the tracer migration induced by the door opening:

$$
\Delta m_{SF6,1} = c_{SF6,2} X_{2\rightarrow 1} = X_{2\rightarrow 1} = \frac{\Delta m_{SF6,1}}{c_{SF6,2}},
$$

(4)

where $\Delta m_{SF6,1}$ is the change in the tracer mass in the anteroom due to tracer migration from the isolation room induced by the door opening, $c_{SF6,2}$ is the steady state concentration of the tracer gas in the isolation room prior to the door opening and $X_{2\rightarrow 1}$ is the air volume migrating across the doorway from the isolation room to the anteroom. When the door closes, the tracer transfer from the isolation room ceases after which the tracer concentration in the anteroom starts to decline back to initial value (i.e. to the value before the door opening). As mentioned previously, the migrated tracer was expected to exit the anteroom only through the exhaust. Hence, the tracer mass in the anteroom reduces according to the exhaust flow rate:

$$
\dot{m}_{SF6,1}(t) = Q_{E,1} \cdot c_{SF6,1}(t),
$$

(5)

where $\dot{m}_{SF6,1}(t)$ is the tracer mass flow rate out of the anteroom, $Q_{E,1}$ is the anteroom exhaust flow rate and $c_{SF6,1}(t)$ the measured tracer concentration in the anteroom exhaust. Integration of the Equation (5), over a period during which the concentration declines back to the initial value, gives the total mass of the tracer migrated from the isolation room to the anteroom:

$$
\Delta m_{SF6,1} = Q_{E,1} \cdot \int_0^T c_{SF6,1}(t) dt.
$$

(6)

Finally, substituting Equation (6) to (4) yields the total air volume transfer through the doorway generated by the door opening:
where $c_{SF6,1,i}$ is the $i$th tracer concentration measurement in the anteroom after the door opening and $\Delta t_i$ is the sampling period of the $i$th measurement. Similarly, an equation can be derived for the air volume transfer from the anteroom to the isolation room.

It should be noted that only the total air volume migration (in m$^3$) through the doorway during the whole door opening can be calculated for each door opening with the tracer gas measurement methods used in this study. The methods do not provide details about the flow rate (in m$^3$/s) as a function of time. However, the temporal evolution is assessed with CFD simulations.

During each experiment (with a set of experimental parameters), the door opening was repeated 5-7 times with approximately an hour interval between the openings. After the door openings were carried out, the tracer supply to the rooms was shut, the rooms were flushed with fresh air, new experimental case set up and subsequently new measurements were initiated. Average results of the air volume exchange for each different case will be reported in this study (along with standard deviation of the results).

In Publication IV the effect of different ventilation rates (0, 6 and 12 ACH), supply-exhaust flow rate differential (pressure difference) and the manikin passage on the airflow patterns and on the air volume exchange were investigated (for hinged and sliding doors). In Publication V the main focus was on examining the effectiveness of 90 L/s and 190 L/s directional airflow (net flow) through the doorway in reducing the total air volume transfer induced by the door opening and passage compared to a reference case without enhanced directional airflow. The effectiveness of the directional airflow was investigated only for the hinged door.

### 2.2 Numerical methods

Computational fluid dynamics (CFD) simulations with complementary experiments were carried out in Publications II and III. The simulations were performed to further characterize the baseline door opening and the manikin passage induced flows across the doorway and to assess the capabilities of CFD simulations to accurately predict the flows. Time-resolved CFD simulations were also expected to provide more detailed information the air volume transfer and flow rate across the doorway as a function of time. Furthermore, the hinged and sliding door induced flows were investigated in separate publications to be able to focus and characterize comprehensively the underlying baseline flow phenomena for one door type at a time. The simulations were restricted to cover only the baseline cases (i.e. without ventilation in use) for both hinged and sliding doors. All simulations were carried out with commercial Ansys CFX software.

The geometry used in the CFD simulations was a copy of the isolation room model used in the experiments in Publication I. The geometry included: two
Methods

26

Rooms, hinged/sliding door (the hinged door was investigated in Publication II and the sliding door in Publication III), manikin and a doorway connecting the two rooms (see Figure 6 for details of the layout).

The mesh of the computational domain was comprised of tetrahedral elements. The total number of the nodes in the hinged door simulation case (Publication II) was 11.7 million nodes (68.7 million elements) and in the sliding door case (Publication III) it was 10.7 million nodes (64.0 million elements). There was a mesh refinement region in the path of the moving manikin and the door. Average element diameter in the refinement region was of the order of 1 cm. The dense mesh was important for the accurate resolving of the air movements but also for the immersed solid method which utilizes the mesh to resolve the surfaces of the moving objects. Four different mesh densities (0.4, 1.3, 10.7 and 15.6 million nodes) was tested in Publication III. It was concluded that increasing the mesh density from 10.7 million nodes provided only minimal change in the results and hence it was decided to use mainly the 10.7 million node mesh in the simulations.

The simulations were carried out using an incompressible time dependent LES solver. In LES turbulent eddies are resolved down to the scale of the grid size and smaller eddies are modelled with sub-grid scale (SGS) models. Wall-Adapting Local Eddy-viscosity (WALE) model was used in the simulations. This model was designed to function well even near solid surfaces (Nicoud, 1999) and it has been successfully used in various modelling scenarios (Jayaraju, 2009; Ducros et al., 2010; Lin et al., 2013). Second order backward Euler and bounded central difference schemes were used in the simulations for time and spatial discretization respectively. The time step length was 0.002 s when modelling the hinged and sliding door openings and the manikin passage but was increased up to 0.03 s when simulating sliding door operation without passage (Publication III).

The geometry was fully surrounded by wall boundary condition (no inlets or outlets to the system). As there were no ventilation present, and initial pressure and velocity components (before the door or manikin motion) were zero everywhere in the domain. Each of the rooms contained different tracer gases (modelled as passive scalars) in the initial state. The air volume migration between

Figure 6. The Geometry of the CFD simulations (Publication II).
the rooms was calculated as in Equations (1)-(3). However, the equations were now significantly simplified (as \( m_{S\text{F},1\rightarrow2} = 0 \) and \( m_{N,0.2\rightarrow1} = 0 \) in the initial state in eq. (1)). The simplified equations are easy to calculate as volume integral functions for the case variables (e.g. for the tracer masses) are readily available in Ansys CFX. Thermal buoyancy effects (when applied) were modelled with Boussinesq approximation.

The movement of the door and the manikin (simulating the human passage through the doorway) were modelled with immersed boundary method (Mittal and Iaccarino, 2005; Choi et al. 2007) called immersed solid technique in Ansys CFX. In this technique, the immersed solid (the volume of the manikin in this case) has its own mesh and if a fluid (node in the underlying domain mesh) is located inside the moving solid, the fluid is forced to move with the solid. Hence the mesh of the immersed solid is not that important as the accuracy of the solid surface depends on the underlying domain mesh density.

### 2.3 Summary of the methods

Table 1 gives a short overview of the main methods and differences between different publications of the thesis.

**Table 1. Summary of the main parameters in different publications (I-V).**

<table>
<thead>
<tr>
<th>Research questions</th>
<th>Publication I</th>
<th>Publication II</th>
<th>Publication III</th>
<th>Publication IV</th>
<th>Publication V</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1, 2, 3 and 4</td>
<td>1 and 3</td>
<td>1 and 3</td>
<td>1, 3 and 4</td>
<td>1,3 and 5</td>
</tr>
<tr>
<td>Investigation type</td>
<td>Experimental</td>
<td>Numerical</td>
<td>Numerical</td>
<td>Experimental</td>
<td>Experimental</td>
</tr>
<tr>
<td>Main investigation method(s)</td>
<td>Smoke visualizations and tracer gas measurements</td>
<td>LES CFD</td>
<td>LES CFD</td>
<td>Smoke visualizations and tracer gas measurements</td>
<td>Smoke visualizations and tracer gas measurements</td>
</tr>
<tr>
<td>Ventilation</td>
<td>No Ventilation</td>
<td>No ventilation</td>
<td>No ventilation</td>
<td>6, 12 ACH</td>
<td>12 ACH</td>
</tr>
<tr>
<td>Supply diffuser type</td>
<td>-</td>
<td>-</td>
<td>Conical/radial</td>
<td>Multi-nozzle</td>
<td></td>
</tr>
<tr>
<td>Directional air flow</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>90, 190 L/s</td>
</tr>
<tr>
<td>Examined door types</td>
<td>Hinged and sliding</td>
<td>Hinged</td>
<td>Sliding</td>
<td>Hinged and sliding</td>
<td>Hinged</td>
</tr>
<tr>
<td>Door opening time (open/hold/close)</td>
<td>Various: 2-8/2-25/3-15 s</td>
<td>3/8/5 s</td>
<td>3/8/5 s</td>
<td>3/8/5 s</td>
<td>3/8/5 s</td>
</tr>
<tr>
<td>Mock-up layout</td>
<td>As in Figure 2</td>
<td>As in Figure 2</td>
<td>As in Figure 2</td>
<td>As in Figure 2</td>
<td>As in Figure 3</td>
</tr>
</tbody>
</table>
3. Results

3.1 Airflow visualizations

In general, the smoke visualizations were carried out to illustrate the airflow patterns in various test cases. However, it should be emphasized that despite their usefulness, all smoke visualizations shown here are only qualitative in nature. For more accurate assessment of the air volume exchange in different cases, quantitative measurements (e.g. tracer gas measurements) are needed to be carried out and analyzed.

3.1.1 Baseline scenario without ventilation

The smoke visualizations for the hinged and sliding doors without ventilation are shown in Figures 7-8. In the figures, subfigures A-D depict the flow patterns on the anteroom side (room 1 in Figure 2) in different instants during the door opening and the manikin passage. The time in the subfigure parenthesis expresses the time passed since the door began to open. Comprehensive smoke visualizations for the baseline cases were reported in Publication I and only a summary is provided here.

The anteroom side-view visualization for the hinged door show that opening creates substantial flow through the doorway (Figure 7 B) and that the wake behind the manikin is difficult to distinguish from the overshadowing impact of the hinged door itself (Figure 7 C). However, smoke can be seen to flow past the manikin and spread around the room after the manikin has stopped (Figure 7 D). This indicates that a substantial amount of air was dragged out of the other room in the wake behind the manikin. The air movements gradually slowed down after the door and manikin motion had seized.

The hinged door opening induced notable smoke spread in horizontal direction as well. Generally, major findings were similar as in the side-view situation, i.e. the door opening generated pronounced flow through the doorway, the effect of the manikin passage (wake) was difficult to distinguish, the air kept moving past the manikin after it had stopped and the motion settled down slowly after the movement of the door and manikin has ended.
Results

Essentially similar large-scale patterns were found in the isolation room side.

Figure 7. Smoke visualization (anteroom side-view) of the airflow patterns across the doorway generated by the hinged door opening and the manikin passage (Publication I).

Figure 8. Smoke visualization (anteroom side-view) of the airflow patterns across the doorway generated by the sliding door opening and manikin passage (Publication I).

Essentially similar large-scale patterns were found in the isolation room side.
Results

(room 2 in Figure 2) as well (i.e. substantial flow through the doorway due to the door motion, wake difficult to distinguish behind the manikin etc.). However, few characteristic patterns were noticed, namely that the door created clear vortices behind the moving door when opening and closing.

Smoke visualizations for the sliding door and manikin passage are illustrated in Figure 8 (anteroom side-view). In contrast to the hinged door case, the opening of the sliding door created only a weak airflow through the doorway and hence the smoke did not spread far from the vicinity of the doorway (Figure 8 B). Also, only modest horizontal scattering of the smoke was seen. However, the manikin movement was found to induce a distinct airflow. That is, the wake was clearly seen behind the manikin, especially behind the waist and upper body (Figure 8 C). The air in the wake continued moving past the manikin and towards the end of the room after the manikin had stopped (Figure 8 D). The airflow diminished gradually after the motion of the door and manikin had stopped. Closing of the sliding door was not seen to induce distinct airflows.

The sliding door opening generated airflows were found to be essentially similar on both side of the door (i.e. in the isolation room and in the anteroom) due to almost symmetrical geometry of the doorway (no large scale sweeping of the door in either rooms). Hence the visualizations of the flows were shown only on one side of the doorway.

3.1.2 Visualizations with ventilation

Smoke visualizations of the door and manikin passage generated airflow patterns with ventilation in use are shown in Figures 9-10. Each subfigure (a-f) illustrates the smoke flow patterns during different phases of the door and manikin passage cycles. The time in the subfigure parenthesis expresses the time passed since the door began to open. Extensive smoke visualizations with ventilation applied were reported in Publication IV and only a summary is given here.

The anteroom side-view of the hinged door opening and manikin passage induced airflow patterns are shown in Figure 9. The door opening motion appeared to generate notable airflow through the doorway (Figure 9 b). However, the flow did not penetrate as far inside to the room as in the baseline case without ventilation. The room airflow patterns appeared to turn the flow towards the ceiling (an upward room airflow was induced by induction air required by the supply jet in the ceiling). The hinged door opening induced flow masked the wake behind the moving manikin (Figure 9 c) but not as much as in the baseline case. A substantial amount of air was carried in the wake which was seen moving past the manikin after it had stopped (Figure 9 d). The closing door was not found to induce notable airflows in the anteroom (Figure 9 e). Generally, it was found that the smoke was spread and mixed quickly in the rooms throughout the experiments due to effective ventilation.

A notable smoke spread was also seen in horizontal direction induced by the hinged door opening and manikin passage, like in the baseline cases. The wake behind the manikin was again masked by the door motion induced airflows. Nevertheless, a notable amount of air was dragged in the wake which was seen
Results

The closing door did not appear to generate notable airflows. The smoke was seen to be spread and mixed rapidly inside the rooms due to effective ventilation.

The hinged door opening generated distinctive flow features on both sides of the doorway. That is, clear door vortices were generated by the sweeping door during opening and closing phases on the isolation room side (not seen on the anteroom side of the doorway described above). Additionally, notable air movement was found to be generated by the closing door on the isolation room side (i.e., to which the door opened into) but not on the anteroom side discussed above.

The sliding door opening and manikin passage induced airflow patterns are shown in Figure 10 (anteroom side-view). The sliding door opening was found to generate only weak flow through the doorway (Figure 10 b), as in the baseline case (see Figure 8 B). The wake behind the moving manikin was now clearly
Results

Figure 10. Smoke visualization (anteroom side-view) of the sliding door opening and the manikin passage induced airflow patterns with 12 ACH ventilation rate and 20 L/s flow rate differential (Publication IV).

visible, especially behind the waist and upper body (Figure 10 c). The manikin appeared to drag a notable amount of air in the wake, which can also be seen moving past the manikin after it had seized (Figure 10 d). The sliding door did not appear to induce any notable air movements on either side of the doorway while closing. A general upward movement of the sliding door opening and manikin passage generated flow features inside the rooms was seen, as in the hinged door case. The smoke was spread, mixed and diluted quickly inside the rooms due to effective ventilation.

The sliding door opening generated airflow was found to be modest also in the horizontal direction and hence the smoke did not spread far from the vicinity of the doorway during the door opening. The wake behind the moving manikin was also distinctly visible on a horizontal plane. The manikin appeared to drag a notable amount of air to the anteroom in the wake. The sliding door motion was not found to induce substantial horizontal airflows in the doorway or inside
the rooms while closing. Additionally, the airflow patterns induced by the sliding door opening were essentially similar on both sides of the doorway and hence the visualizations were shown only on one side of the doorway. Again the smoke was quickly spread, mixed and diluted inside the rooms due to effective ventilation, like in the other cases when the ventilation was in use.

### 3.1.3 Visualizations with directional airflow

Smoke visualization of the airflow patterns with and without directional airflow are shown in Figures 11-12. The airflow patterns in different phases of the door opening cycle are illustrated in subfigures (a-d). As in the previous visualizations, the time in the parenthesis expresses the time elapsed after the door started to open. Comprehensive smoke visualizations for the baseline cases were reported in Publication V.

The hinged door opening and manikin passage induced airflows without directional airflow are illustrated in Figure 11. Like in previous cases with the hinged door, the opening created a drastic airflow across the doorway (Figure 11 b). Due to a small anteroom size, the smoke penetrated almost to the other

![Image](image-url)

**Figure 11.** Smoke visualization (anteroom side-view) of the airflow patterns generated by the hinged door opening and the manikin passage in the reference case (no directional airflow or temperature difference between the rooms) (Publication V).
Results

end of the room. The passage generated wake was now completely overshadowed by the door opening induced smoke flow (Figure 11 c). The smoke was quickly mixed throughout the room (Figure 11 c-d).

The hinged door opening and manikin passage induced airflows with 190 L/s directional airflow are illustrated in Figure 12. The door opening was found to cause detectable airflow out of the isolation room into the anteroom despite the directional air flow towards the isolation room (Figure 12 b). However, the enhanced directional airflow appeared to reduce the air escape from the isolation room (in all different phases of the opening and passage cycles, Figure 12 b-d) compared to the reference case without directional ventilation applied (Figure 11).

3.2 Tracer gas measurements

Tracer gas measurements were carried out to quantify the total air volume exchange through the doorway induced by the door opening and manikin passage in three different scenarios: without ventilation, with ventilation, and with en-
hanced directional airflow (net flow). Also, the effect of other door opening related factors (all tested cases are described in Tables 2-4) on the doorway exchange flows were examined with the tracer gas measurements.

### 3.2.1 Air volume transfer in the baseline scenario without ventilation

Baseline experiments characterizing the elementary flows generated by the door opening and manikin passage (without mixing effect of ventilation) were carried out and studied in Publication I. Summary of the tracer gas measurement results (i.e. the average air volume transfer through the doorway) for the baseline cases for both door types (hinged and sliding) are shown in Table 2 and visualized in Figure 13. The air volume migration from the room 1 (anteroom) to the room 2 (isolation room) is marked with $X_{1\rightarrow2}$ and to the opposite direction with $X_{2\rightarrow1}$ in the tables and figures.

The first section of Table 2 shows that the hinged and sliding doors induced 1.39 m$^3$ and 0.56 m$^3$ air volume migration out of the isolation room respectively. Hence the sliding door generated air volume transfer was 0.83 m$^3$ smaller on average compared to the hinged door (i.e. 60 % reduction). The first section of Table 2 also shows that, for each door type separately, the average air volume migration to both directions across the doorway were similar.

The air volume flow through the doorway was reduced to 1.16 m$^3$ and 0.34 m$^3$ (i.e. 17 % and 39 % reduction) with hinged and sliding doors respectively, when the opening gap was decreased to half (see the second section of Table 2). However, it should be noted that the door opening times were not the same for hinged and sliding doors in this case due to limitations in the automatic door openers.

Door opening speed seemed to affect the air volume exchange slightly. The results are shown in the third section of Table 2 and illustrated in the top left corner of Figure 13. Similar trend can be seen with both door hold-open times (i.e. 2 s and 8 s). However, the effect of total cycle time is not removed from these figures and this should be taken into account before making final conclusions.

Results with different door hold-open times are shown in Table 2 (fourth section) and visualized in Figure 13 (top right corner). The air volume transfer was found to increase with the hold-open time for both door types. Similar trend was found also with the door total cycle time (comparison of several opening, hold-open and closing times), i.e. the longer the total cycle time the greater the air volume exchange across the doorway with both door types.

Temperature difference appeared to have a notable effect on the air volume transfer through the doorway. The air volume migration with 2 °C temperature difference between the rooms was 1.96 m$^3$ for the hinged door and 2.26 m$^3$ for the sliding door. The increase (1.70 m$^3$) was much more substantial for the sliding door (304 % increase) than for the hinged door (0.57 m$^3$ or 41 % increase) compared to the baseline case without temperature difference. The results are shown in Table 2 (fifth section) and illustrated in Figure 13 (bottom left corner).
The effect of the passage for both door types are shown in Table 2 (bottom section) and visualized in Figure 13 (bottom right corner). The effect of the passage on the air volume migration was found to be notable. Based on the measurements the average air volume exchange induced by the passage (to both directions) was 0.26 m³ and 0.36 m³ (i.e. 19 % and 64 % increase compared to the case without passage) for hinged and sliding doors, respectively.

The passage direction had a notable effect on the air volume migration, especially with the hinged door. That is, the exit from the isolation room (room 2)
induced 1.93 m³ air volume exchange across the doorway, which was substantially higher compared to the exchange of 1.37 m³ with passage to the other (entry) direction. No clear effect regarding passage direction was found with the sliding door.

### 3.2.2 Air volume transfer with ventilation

The effects of ventilation and pressure difference on the air volume exchange and airflow patterns across the doorway induced by the door opening and manikin passage were investigated in Publication IV. The tracer gas measurement results and related air volume migrations are shown in Table 3 and visualized in Figure 14. The focus of the experiments was on the air volume escaping from the isolation room to the anteroom (i.e. marked with $X_{2\rightarrow1}$ in Table 3).

The effect of 0, 6 and 12 ACH (without pressure difference and manikin passage between the rooms) is shown in the first subsection of Table 3 and illustrated in Figure 14 top left corner. As in the baseline scenarios without ventilation, there was a notable difference in the air volume exchange across the doorway generated by the opening of the hinged and sliding doors. The hinged door motion induced an air volume exchange of 1.45 m³ and 1.47 m³ through the
Table 3. Tracer gas measurement results of the air volume transfer through the doorway with different ventilation rates applied (0, 6 and 12 ACH) (Publication IV).

<table>
<thead>
<tr>
<th>Door type</th>
<th>Door cycle time (open/hold/close)</th>
<th>Air change rate(^a) [ACH]</th>
<th>Flow diff.(^b) [L/s]</th>
<th>Passage</th>
<th>Avg. air volume transfer</th>
<th>STD</th>
<th>Normalized air flow(^f)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X(_{1\rightarrow2})</td>
<td>X(_{2\rightarrow1})</td>
<td></td>
</tr>
<tr>
<td>With different air changes per hour:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>[m(^3)]</td>
<td>[m(^3)]</td>
<td></td>
</tr>
<tr>
<td>Hinged</td>
<td>3/8/5.4</td>
<td>0</td>
<td>0 (0)</td>
<td>0.54</td>
<td>0.56</td>
<td>0.07</td>
<td>0.28</td>
</tr>
<tr>
<td>Sliding</td>
<td>3/8/5.4</td>
<td>0</td>
<td>0 (0)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Hinged</td>
<td>3/8/5.4</td>
<td>6.1</td>
<td>c. 0 (0)</td>
<td>-</td>
<td>1.32</td>
<td>1.45</td>
<td>0.13</td>
</tr>
<tr>
<td>Sliding</td>
<td>3/8/5.4</td>
<td>6.1</td>
<td>c. 0 (0)</td>
<td>-</td>
<td>0.42</td>
<td>0.27</td>
<td>0.07</td>
</tr>
<tr>
<td>Hinged</td>
<td>3/8/5.4</td>
<td>12.2</td>
<td>c. 0 (0)</td>
<td>-</td>
<td>1.54</td>
<td>1.47</td>
<td>0.12</td>
</tr>
<tr>
<td>Sliding</td>
<td>3/8/5.4</td>
<td>12.4</td>
<td>c. 0 (0)</td>
<td>0.76</td>
<td>0.84</td>
<td>0.20</td>
<td>0.42</td>
</tr>
<tr>
<td>With pressure difference:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hinged</td>
<td>3/8/5.4</td>
<td>6.1</td>
<td>25 (-21)</td>
<td>-</td>
<td>-</td>
<td>1.17</td>
<td>0.17</td>
</tr>
<tr>
<td>Sliding</td>
<td>3/8/5.4</td>
<td>6.0</td>
<td>25 (-21)</td>
<td>-</td>
<td>0.27</td>
<td>0.09</td>
<td>0.13</td>
</tr>
<tr>
<td>Hinged</td>
<td>3/8/5.4</td>
<td>12.0</td>
<td>18 (-21)</td>
<td>-</td>
<td>-</td>
<td>1.31</td>
<td>0.22</td>
</tr>
<tr>
<td>Sliding</td>
<td>3/8/5.4</td>
<td>12.2</td>
<td>21 (-21)</td>
<td>-</td>
<td>0.54</td>
<td>0.17</td>
<td>0.27</td>
</tr>
<tr>
<td>With passage:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hinged</td>
<td>3/8/5.4</td>
<td>6.0</td>
<td>22 (-21)</td>
<td>Both dir.</td>
<td>-</td>
<td>1.51</td>
<td>0.16</td>
</tr>
<tr>
<td>Sliding</td>
<td>3/8/5.4</td>
<td>6.1</td>
<td>24 (-21)</td>
<td>Both dir.</td>
<td>-</td>
<td>0.50</td>
<td>0.06</td>
</tr>
<tr>
<td>Hinged</td>
<td>3/8/5.4</td>
<td>6.0</td>
<td>23 (-21)</td>
<td>2(\rightarrow)1</td>
<td>-</td>
<td>1.62</td>
<td>0.05</td>
</tr>
<tr>
<td>Sliding</td>
<td>3/8/5.4</td>
<td>6.1</td>
<td>24 (-21)</td>
<td>2(\rightarrow)1</td>
<td>-</td>
<td>0.49</td>
<td>0.09</td>
</tr>
<tr>
<td>Hinged</td>
<td>3/8/5.4</td>
<td>6.0</td>
<td>21 (-21)</td>
<td>1(\rightarrow)2</td>
<td>-</td>
<td>1.34</td>
<td>0.05</td>
</tr>
<tr>
<td>Sliding</td>
<td>3/8/5.4</td>
<td>6.1</td>
<td>25 (-20)</td>
<td>1(\rightarrow)2</td>
<td>-</td>
<td>0.50</td>
<td>0.04</td>
</tr>
<tr>
<td>Hinged</td>
<td>3/8/5.4</td>
<td>12.0</td>
<td>18 (-21)</td>
<td>Both dir.</td>
<td>-</td>
<td>1.56</td>
<td>0.21</td>
</tr>
<tr>
<td>Sliding</td>
<td>3/8/5.4</td>
<td>12.2</td>
<td>20 (-22)</td>
<td>Both dir.</td>
<td>-</td>
<td>0.78</td>
<td>0.14</td>
</tr>
<tr>
<td>Hinged</td>
<td>3/8/5.4</td>
<td>12.0</td>
<td>18 (-21)</td>
<td>2(\rightarrow)1</td>
<td>-</td>
<td>1.58</td>
<td>0.26</td>
</tr>
<tr>
<td>Sliding</td>
<td>3/8/5.4</td>
<td>12.2</td>
<td>21 (-22)</td>
<td>2(\rightarrow)1</td>
<td>-</td>
<td>0.82</td>
<td>0.20</td>
</tr>
<tr>
<td>Hinged</td>
<td>3/8/5.4</td>
<td>12.0</td>
<td>18 (-21)</td>
<td>1(\rightarrow)2</td>
<td>-</td>
<td>1.54</td>
<td>0.18</td>
</tr>
<tr>
<td>Sliding</td>
<td>3/8/5.4</td>
<td>12.2</td>
<td>19 (-22)</td>
<td>1(\rightarrow)2</td>
<td>-</td>
<td>0.73</td>
<td>0.07</td>
</tr>
</tbody>
</table>

\(^a\) Measured from the isolation room exhaust (both rooms had the same ventilation rates)
\(^b\) Flow rate differential (supply-exhaust) between rooms while door open
\(^c\) Pressure difference between the rooms before door opening (isolation room in lower pressure)
\(^d\) X\(_{1\rightarrow2}\): air volume migration from the room 1 (anteroom) to the room 2 (isolation room)
\(^e\) X\(_{2\rightarrow1}\): air volume migration from the room 2 (isolation room) to the room 1 (anteroom)
\(^f\) Normalized by the swept volume of the hinged door (1/4\(\pi\)w\(^2\)h\(_{\text{door}}\))

The effect of ventilation rate on the air volume exchange appeared to be small with the hinged door, i.e. the results were almost the same with 0, 6 and 12 ACH. The sliding door opening generated air volume migration across the doorway with 6 and 12 ACHs respectively. Hence the sliding door opening generated air volume exchange was 1.03 m\(^3\) and 0.63 m\(^3\) smaller (i.e. 71 % and 43 % reduction with 6 and 12 ACHs respectively) compared to the hinged door case. The results show that there were no large differences in the air volume migration directions (X\(_{1\rightarrow2}\) or X\(_{2\rightarrow1}\)) across the doorway with both door types.

The effect of an air volume exchange rate on the air volume exchange appeared to be small with the hinged door, i.e. the results were almost the same with 0, 6 and 12 ACH. However, some variation was found with the sliding door. The air volume migration was found reduce with 6 ACH compared to the 0 ACH case. On the other hand, with 12 ACH the air exchange volume was found to increase compared to 6 ACH case.

The effect of 20 L/s supply-exhaust flow rate differential (i.e. 20 L/s net flow across the doorway when doors were open or 20 Pa pressure difference when
doors were closed) without the manikin passage is shown in the second subsection of Table 3 and illustrated in Figure 14 top right corner. The air volume exchange was 1.17 m³ and 1.31 m³ with 6 and 12 ACHs (both with 20 L/s supply-exhaust flow rate differential), respectively, for the hinged door. That is, the air volume migration was reduced by 0.28 m³ and 0.16 m³ (i.e. 19 % and 11 % reduction) with 6 ACH and 12 ACH ventilation rates, respectively, compared to the case without supply-exhaust flow rate differential. For the sliding door the air volume exchange was 0.27 m³ and 0.54 m³ with 6 and 12 ACHs (both with 20 L/s supply-exhaust flow rate differential), respectively. Hence the reduction was 0.15 m³ and 0.30 m³ (i.e. 36 % reduction) with 6 and 12 ACHs, respectively, compared to the case without supply-exhaust flow rate differential.

The air volume exchange results with the manikin passage are shown in the last section of Table 3 and illustrated in Figure 14 bottom left corner for both door types with both ventilation rates. The effect of the passage on the air volume migration was found to be notable, like in the baseline scenario without ventilation. Additional air volume transfer across the doorway induced by the manikin passage was measured to be 0.34 m³ and 0.25 m³ (i.e. 29 % and 19 % increase compared to the cases without passage) with 6 and 12 ACHs, respectively, for the hinged door. Similarly, the additional air volume migration induced by the manikin passage was found to be 0.23 m³ and 0.24 m³ (i.e. 85 % and 44 % increase compared to the cases without passage) with 6 and 12 ACHs, respectively, for the sliding door. The air volume exchange appeared to be almost independent of the manikin movement direction (as illustrated in Figure 14 bottom right corner). Only the manikin exit (2→1) appeared to induce greater total volume transfer than the entry with 6 ACH with the hinged door.

Figure 14. Air volume exchange across the doorway in various scenarios with different ventilation rates (0, 6 and 12 ACH) applied (Publication IV).
3.2.3 Air volume transfer with directional airflow

The effect of enhanced directional airflow (net flow) on the air volume exchange across the doorway induced by the hinged door opening and manikin movement was investigated in Publication V. The tracer gas measurement results are summarized in Table 4 and illustrated in Figure 15. As with the previous cases, the focus was on the air volume migration from the isolation room to the anteroom (i.e. $X_{2\rightarrow1}$ in Table 4).

The first two sections of Table 4 shows that the average air volume migration in the reference cases (baseline cases) generated by the door opening with and without the manikin movement were found to be 1.29 m$^3$ and 1.03 m$^3$ respectively. Hence the effect of the manikin motion was 0.26 m$^3$ (i.e. 25 % increase) on average.

The second section of Table 4 shows also that the air volume migration from the isolation room to the anteroom was found to be 0.80 m$^3$ and 0.51 m$^3$ with the 90 L/s and 190 L/s directional airflow rates respectively. Hence the reduction in the air volume transfer was found to be 0.49 m$^3$ and 0.78 m$^3$ (i.e. 38 % and 60 % reduction) on average compared to the reference (baseline) case without directional airflow. The results are illustrated in Figure 15 (on the left).

The results of the air volume exchange with the 3 °C temperature difference (between the rooms) are shown in the lowest section of Table 4 and illustrated in Figure 15 (on the right). The average air volume transfer from the isolation room to the anteroom with the temperature difference (higher temperature at the isolation room) was found to be 2.34 m$^3$. Hence the temperature difference increased the air volume migration by 1.05 m$^3$ (i.e. 81 % increase) on average compared to the reference case without temperature difference. The air volume migration induced by the door opening, manikin movement and 3 °C temperature difference was found to be 1.62 m$^3$ and 1.42 m$^3$ with the 90 L/s and 190 L/s directional airflow scenario.

Table 4. Tracer gas measurement results of the air volume transfer across the doorway with and without directional airflow applied (Publication V).

<table>
<thead>
<tr>
<th>Case</th>
<th>Door cycle time (open/hold/ close) [s]</th>
<th>Avg. directional airflow$^a$ [L/s]</th>
<th>Avg. press. diff.$^b$ [Pa]</th>
<th>Avg. temp. diff.$^b$ [°C]</th>
<th>Number of repeats</th>
<th>Avg. air volume transfer $X_{2\rightarrow1}$ [m$^3$]</th>
<th>Standard error (SE)$^d$ [m$^3$]</th>
<th>Relative air volume transfer$^e$ (isol$\rightarrow$ante)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Door opening without manikin passage:</td>
<td>3/8/5.4</td>
<td>4</td>
<td>-20</td>
<td>0.2</td>
<td>6</td>
<td>1.03</td>
<td>0.04</td>
<td>0.53</td>
</tr>
<tr>
<td>Baseline</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Door opening with manikin passage:</td>
<td>3/8/5.4</td>
<td>3</td>
<td>-19</td>
<td>0.0</td>
<td>6</td>
<td>1.29</td>
<td>0.07</td>
<td>0.66</td>
</tr>
<tr>
<td>Baseline</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Directional airflow scenario</td>
<td>3/8/5.4</td>
<td>90</td>
<td>-20</td>
<td>0.1</td>
<td>6</td>
<td>0.80</td>
<td>0.11</td>
<td>0.41</td>
</tr>
<tr>
<td>Directional airflow scenario</td>
<td>3/8/5.4</td>
<td>190</td>
<td>-20</td>
<td>0.1</td>
<td>6</td>
<td>0.51</td>
<td>0.04</td>
<td>0.26</td>
</tr>
<tr>
<td>Door opening with manikin passage and temperature difference:</td>
<td>3/8/5.4</td>
<td>4</td>
<td>-19</td>
<td>2.9</td>
<td>6</td>
<td>2.34</td>
<td>0.22</td>
<td>1.20</td>
</tr>
<tr>
<td>Baseline</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Directional airflow scenario</td>
<td>3/8/5.4</td>
<td>90</td>
<td>-20</td>
<td>2.8</td>
<td>6</td>
<td>1.62</td>
<td>0.13</td>
<td>0.83</td>
</tr>
<tr>
<td>Directional airflow scenario</td>
<td>3/8/5.4</td>
<td>190</td>
<td>-18</td>
<td>2.8</td>
<td>6</td>
<td>1.42</td>
<td>0.13</td>
<td>0.73</td>
</tr>
</tbody>
</table>

$^a$ Door open
$^b$ Door closed
$^c$ $X_{2\rightarrow1}$: air volume migration from the isolation room to the anteroom
$^d$ $SE = STD / \sqrt{N}$ where STD is standard deviation and N the number of measurements/repeats
$^e$ Air volume transfer ($X_{2\rightarrow1}$) divided by the swept volume of the door ($1/4\pi W_{\text{door}}^2 H_{\text{door}}$)
Results

The air volume transfer across the doorway in reference (baseline) and directional airflow (forced airflow) cases (Publication V).

directional airflows respectively. Hence the the air volume migration was reduced by 0.72 m³ (31 %) and 0.92 m³ (39 %) with 90 L/s and 190 L/s directional airflow rates respectively, compared to the case without directional airflow. Thus, the reduction was only 0.20 m³ between the directional airflow cases. Nevertheless, the examined the directional airflow rates through the doorway appeared to limit the 3 °C temperature difference driven flow during the door opening substantially. However, the additional reduction gained by the higher directional airflow was only small and the reasons for this needs to be studied further in the future.

3.3 CFD simulations

3.3.1 Hinged door simulations

The hinged door simulations with supplementary experiments are presented, investigated and discussed in detail in Publication II. Comparison of experimental and simulated smoke visualizations (based on simulated tracer gas concentration isosurfaces with different transparencies) are shown in Figures 16-17. Figure 16 shows the isolation room top-view of the smoke flow across the doorway to the isolation room at the end of the door opening cycle (before the manikin moves through the doorway). Figure 17 shows the smoke flow through

Figure 15. The air volume transfer across the doorway in reference (baseline) and directional airflow (forced airflow) cases (Publication V).

Figure 16. Experimental and simulated smoke visualizations (on the left and right respectively) of the nurse exiting the isolation room (Publication II).
the doorway to the anteroom generated by the hinged door opening and manikin movement. From the figures one can see that both methods (experimental and simulated smoke visualizations) depict essentially similar flow structures (although some differences can be found): opening of the door generates vortex behind opening door (Figure 16); air is drawn through the doorway in the wake of the manikin etc.

Temporal evolution of the air volume transfer across the doorway induced by the door motion alone and by the combined effect of the door and manikin movement can be seen in Figure 18. From the bottom figure one can see that in the early opening phase the air volume transfer increases rapidly due to the door opening generated impulse. However, only after 1-2 seconds the air volume migration across the doorway stabilizes and then grows steadily over the rest of the door opening cycle until the door has closed again. The closing phase of the door
Results

opening cycle does not seem to affect the air volume exchange notably. The CFD simulation result for the door only seemed to be rather close to the measured values. From the top part of the Figure 18 one can see the effect of the manikin passage on the air volume exchange. The manikin passage increases the air volume exchange notably but about 3-4 s after manikin passage, the growth becomes steady again. As in the case without passage, closing phase of the door cycle was not found to affect the air volume exchange notably.

3.3.2 Sliding door simulations

The sliding door simulations with complementary experiments were introduced, analyzed and discussed in detail in Publication III. Comparison of the experimental and simulated smoke visualizations for the sliding door case are shown in Figures 19-20. The door opening induced flows (without the effect of the manikin passage) can be seen in Figure 19 with different mesh sizes (i.e. densities). From the figure one can see that vortices are formed in the doorway by the sliding door motion which mixes the air in the doorway and hence induces some air transfer across the doorway. Similar vortex structures can be seen both in the experimental and simulation visualizations. However, the coarse mesh (1.3 M nodes) produced much simpler flow structure in the doorway compared to the denser meshes (it was not able to simulate the eddy formation as accurately as the denser meshes).

The door opening and manikin passage generated air flows across the doorway can be seen in Figure 20. Experimental and simulated flow structures were quite similar. Both depict wake, door opening etc. induced flows on both sides of the doorway. The effect of passage seems to be notable and the airflow generated by it seemed to dominate the air transfer across the doorway.

Figure 21 shows the temporal evolution of the air volume transfer across the doorway induced by the door and manikin motion. The upper part depicts the

![Flow structures (vortices) at the doorway generated by the sliding door opening (Publication III).](image)
Results

Figure 20. Comparison of the simulated smoke visualization (on the left) and experimental smoke visualizations (on the right) (Publication III).

Figure 21. Temporal evolution of the air volume migration (on the top) and the volume flow rate (at the bottom) (Publication III).

The flow rate across the doorway can be seen on the bottom part of Figure 21. The door opening and manikin passage both generated notable flow rate through the doorway. However, the manikin passage induced more sudden, impulse like flow rate change than the sliding door opening motion. The flow rate evolution of the total transfer volume and the lower part the flow rate as a function of time. From the upper part one can see that about 0.40 m³ of air flows across the doorway (before the manikin moves across the doorway). The manikin movement accelerates the air volume exchange notably when moving through the doorway. Even the backflow (i.e. the flow across the doorway generated by the volume displaced by the manikin when it enters the room) generated by the manikin can be seen clearly. The total exchange volume was found to be 0.88 m³ and hence relatively well in line with the experiments.
through the doorway slowly reduces towards zero after the door opening and manikin passage. Closing phase of the door movement did not seem to increase the flow across the doorway.

The effect of temperature difference on the air volume transfer across the doorway during the door opening was also investigated in Publication III. Already small temperature difference (0.2 °C) was found to induce notable increase to air volume transfer across the doorway compared to the case without temperature difference. With 2 °C temperature difference the air volume was found to rapidly increase the air volume migration even in the very early phase of the door opening cycle. The rapid acceleration of the temperature difference driven flow in the beginning of the opening cycle was probably due to small disturbance caused to the flow field by the sliding door opening itself.
4. Discussion

A careful and systematic examination of the air volume exchange and airflow patterns through doorways induced by the door opening and manikin passage has been carried out in this thesis. Several factors (like hinged and sliding door opening, door opening/hold-open/cycle times, passage, temperature difference, ventilation rate, supply-exhaust flow rate differential (pressure difference) and enhanced directional airflow) and their effects related to exchange flows across a doorway separating two spaces has been investigated. Better understanding of the parameters and factors governing the flows can enable better control and hence reduction of the exchange flows. This can be beneficial especially in cases where the exchange flows can have serious consequences to health, like in the breakdown of isolation conditions in healthcare settings. Reduction of the exchange flows can have beneficial impact also in other application areas, like in limiting contaminant and particle penetration to industrial cleanrooms, warm air entering cold storages etc. where strict containment conditions are required. Many of the factors studied in this thesis have been found to have a substantial effect on the doorway air flows. The results, implications of the findings and limitations of this study are discussed below.

4.1 Airflow patterns

Smoke experiments and CFD simulations were used to visualize the airflow patterns across the doorway. Smoke has been applied widely in fluid flow visualizations (Smits and Lim 2000). It offers a simple and versatile method to examine flow features even with great detail. Although often used only for qualitative assessment of a flow field, smoke visualizations can still prove to be very useful for providing a clear picture about the main characteristics of the studied phenomena. This section discusses the results related to the research questions 1, 3, 4 and 5 from the qualitative point of view.

The visualizations examined in this thesis provided clear picture of the principal flow structures induced by the hinged and sliding door opening. The structures were highlighted most clearly in the baseline visualizations without ventilation in use. Although investigating the doorway flows without ventilation can be considered idealistic, they were still regarded important for the characterization of the fundamental flow structures. The results presented in this thesis (Publications I-III) explicitly show that: the hinged door opening induced a
drastic flow across the doorway reaching far inside the rooms; the sliding door opening induced a modest flow affecting only the vicinity of the doorway; the manikin movement induced wake was clearly visible with the sliding door and it was found to increase the airflow through the doorway notably; the air in the wake was dragged and spread far inside the rooms by the moving manikin; the hinged door formed clear door vortices behind the opening and closing door.

On the other hand, the airflow patterns were affected by the ventilation. In general, ventilation appeared to mix and dilute the smoke throughout the room effectively. Hence the smoke was seen to spread rapidly around the rooms and the flow structures (door opening generated structures, wake of the manikin etc.) lost their form quickly due to effective ventilation. Nevertheless, based on the qualitative assessment of the smoke visualizations alone, it was difficult to distinguish whether the ventilation or flow rate differential used in the experiments increased or reduced the flow through the doorway compared to the base-line case without ventilation.

Small-scale water models and CFD techniques have been widely used to investigate and visualize the door opening generated flows (Kiel and Wilson, 1989; Tang et al., 2005; Shih et al., 2007; Eames et al., 2009; Tung et al., 2009; Hang et al., 2015; Hathway et al., 2015; Mousavi et al., 2016; Chang et al., 2016, 2017; Lee et al., 2016; Papakonstantis et al., 2018; Sadrizadeh et al., 2018). Many of the studies have provided illustrative visualizations of the airborne contaminant spreading due to door opening. However, many of the studies focus only on one door type (either hinged or sliding), only to the effect of the door (excluding passage), or to cases without ventilation applied and hence do not provide as profound, systematic and detailed view of the phenomena as supplied in Publications I-V in this study.

Actually, there are only a limited number of studies that have visualized the differences of hinged and sliding doors (Choi and Edwards, 2012; Tang et al., 2013; Lee et al., 2016; Sadrizadeh et al., 2018). In general, they have reported similar findings as found in this thesis. However, common to many studies is that they have been carried out in scale models or by CFD simulations and hence lack experimental full-scale visualizations altogether, which makes the visualizations presented in this thesis unique and a baseline for future studies.

General flow features of the directional airflow were also examined in this thesis. The flow structures appeared to be rather similar compared to the other examined cases with and without ventilation applied. That is, the hinged door opening induced notable airflow through the doorway, passage increased the airflow etc. However, the directional airflow seemed to reduce the overall air transfer across the doorway (although not completely preventing it, at least with the directional airflow rates tested). Similar findings have also been reported by Hendiger et al. (2016). They carried out a qualitative visualization of the flow of heavy contaminants along the floor across the doorway caused by a hinged door opening and human movement. They found that the door opening and occupant movement generated contaminant flow across the doorway even with notable directional airflow (net flow) through the doorway. Nevertheless, they also concluded that the heavy contaminant transfer can be reduced by the net airflow
through the door opening but that up to 0.6–1.0 m/s airflow would be needed to completely block the escape induced by the door pumping effect and human movement.

Wang et al. (2019) examined the effect of increased directional airflow across an OR doorway (without occupant movement). Although they did not carry out any experimental visualizations, their CFD simulations showed that temporarily lowering the OR exhaust flow (i.e., creating an increased directional airflow out of the OR) during a sliding door opening can be an effective method to reduce the airborne bacteria carrying particle intrusion to the OR.

The directional airflow across the doorway seems to be a promising method to reduce detrimental penetration of airborne contaminants through doorways. However, it still remains unclear how high directional airflow is needed to reduce the airflow across the doorway close to zero and how realistic it is to reach those airflow rates quickly enough to respond to the transient effects induced by the door opening.

It should be noted that the smoke visualizations examined in this thesis were only qualitative in nature and based on them it is difficult to estimate the amount of smoke/air flowing across the doorway. In order to get more comprehensive and fundamental view of the air volume exchange generated by the door opening, a quantitative assessment needs to be carried out. In this thesis tracer gas measurements were carried out to quantitatively assess the air volume transfer across the doorway.

4.2 Effect of different factors on the air volume exchange through doorways

Extensive tracer gas measurements were carried out in this thesis to assess the air volume exchange across the doorway induced by the door opening and manikin movement. The results show that several different parameters affected the air volume transfer across the doorway notably. The main findings are discussed here and put into context with earlier studies in this field of research. This section also provides discussion and reflection of the findings related to the research questions (1–5) from the quantitative point of view.

4.2.1 Swept volume of the door

One of the clearest findings of the tracer gas measurements was that the sliding door generated significantly smaller air volume exchange through the doorway than the hinged door (supporting the findings of the smoke visualizations). The greater air volume migration produced by the hinged door is somewhat intuitive as it generates more drastic air motion in the doorway by sweeping a larger area and hence pulling more air behind it across the doorway than the sliding door.

In fact, some studies have used the volume swept by a door as a proxy for the air volume exchange across a doorway. For instance, according to a small-scale water model study by Kiel and Wilson (1989) the typical exchange volume is about 50% of the swept volume of the door. On the other hand, Eames et al. (2009) and Fontana and Quintino (2014) found (also using a small-scale water
model) the transferred volume to be comparable (but smaller) to the swept volume of the door. Hathway et al. (2015) also used a small-scale water model to examine a hinged door opening motion generated exchange volume between two identical rooms. They found the hinged door opening motion induced exchange to be 67-98% of the swept volume of the door (depending on the door hold-open time). Papakonstantis et al. (2018), also using a small-scale water model, found that the average exchange volume normalized by the swept volume of the door varied from 70% to 130% depending on the door hold-open time.

Here the measured range of the air volume exchange was 59-124% and 15-115% of the swept volume for hinged and sliding doors respectively (both normalized with the swept volume of the hinged door) without ventilation (Publication I). The normalized air volume exchange was found to vary between 58-81% for the hinged door and between 13-42% for the sliding door when ventilation was taken into account (Publication IV). Similar range of results was found by Hayden et al. (1998), who examined the hinged and sliding door induced air volume migration through a doorway in a full-scale hospital isolation room model. They found that the opening of a hinged door generated 47–67% air exchange (depending on the flow rate differential) between the isolation room and the adjacent anteroom (both with ventilation). Similarly, for the sliding door they found the air volume migration to be 16-49% of the swept volume of the hinged door (on average, without passage and depending on the flow rate differential).

The air volume exchange results for the sliding door are still somewhat notable despite being substantially smaller compared to the hinged door. It was expected (a priori) that a sliding door would induce only a flow of a few hundred litres of air through the doorway (at maximum), especially in the baseline cases when ventilation was not in use. Nevertheless, a sweeping door, regardless of the door type, seems to have an effect on the induced exchange flows. However, reduction of the swept volume appears to decrease the airflow through the doorway substantially. Actually, Fontana and Quintino (2014) have found that the mass transfer is not directly proportional to the swept volume of the hinged door but that the ratio tended to grow while the swept volume reduced. However, there seems to be no data for the sliding door results as almost all of the previous studies have focused on hinged doors induced flows.

Although the swept volume of the door can be considered as a good first proxy of the total air volume migration across the doorway, it was noticed, in fact, that several parameters affected the exchange, like the door hold-open time, temperature difference, movement through the doorway etc., which should be taken into account.

### 4.2.2 Door opening speed and hold-open time

In general, after the door opening has set the air in motion across the doorway, the air transfer continues until the door generated momentum dies out (in the absence of other driving forces such as temperature difference) or the door is closed. This supposition is supported by the baseline scenario (without ventila-
results of this study, as it was found e.g. that the air volume exchange increased with increasing hold-open time. Similar trend was seen with the total cycle time.

Similar findings have been reported by Hathway et al. (2015) and Papakonstantis et al. (2018), who examined a hinged door opening induced exchange volume through a doorway in a small-scale water model. They concluded also that the exchange volume increases with the door hold-open time. These results are further supported by the CFD simulations carried out in this study (Publications II and III). For instance, the results in Publication II show that after the initial phase of the hinged door opening cycle, the rate of air volume exchange was almost constant throughout the door opening cycle until the door closed (this was seen with both door types). Unfortunately, the CFD simulations were not repeated with different door speeds or hold-open times to see whether this holds for other scenarios as well. However, passage increased the rate of air volume exchange momentarily but after a few seconds the flow rate settled to a constant value again. The rate of air volume exchange was also almost constant with the sliding door (during door hold-open phase) but that it had a notably lower value than with the hinged door.

Another factor that is typically considered to have an effect on the exchange flows is the door opening speed. It is often supposed that increasing the door opening speed increases the air volume transfer due to higher momentum and air velocities generated at the doorway. However, this is still somewhat unclear. The results gained in this study imply that the door opening speed does not have a notable effect on the air volume transfer across the doorway. Rather, the results support opposite effect, i.e. the air volume exchange reduces the faster the door opening is. One explanation for this could be that with a higher opening speed the total cycle time decreases which was found to reduce the air volume exchange across the doorway. If the total cycle time trend is removed from the opening time results, the adjusted results show only a slight effect of the opening time on the air volume transfer. Hence one could argue that the exchange is not substantially affected by the door opening time/speed. Similar effect was found both with the hinged and sliding doors in this study.

On the other hand, Kiel and Wilson (1989) found out that increasing the speed of a hinged door increased the exchange volume through the doorway. They studied the exchange flows through an outer door of a mock-up house in small-scale water model and scaled their results according to densimetric Froude number similarity. If the data is scaled based on Reynolds number similarity (see e.g. Papakonstantis et al. (2018)), which should be valid for zero buoyancy (temperature difference) case, it can be seen that Kiel and Wilson (1989) used much lower door opening speeds than examined in this thesis. Hence one should be cautious when comparing their results with the ones presented in this study.

Other studies have found that the exchange volume induced by a hinged door opening does not vary notably with door speed (with door angular speeds in the range of 10-30 deg/s). For instance, Hayden et al. (1998) concluded in their study that the air volume migration generated by a hinged door opening did not
change notably when door opening time was increased from 5 s to 8 s and closing time from 8 s to 12 s (with constant hold-open time of 2 s). However, they carried out their study under the influence of ventilation and pressure difference between the rooms and it might be that due to those effects the true effect of the plain door opening with respect to time cannot be observed.

Additionally, supporting evidence to this thesis results was also found by Papakonstantis et al. (2018). They found out that the exchange volume induced by a hinged door did not vary considerably with door opening speed.

Although the effect of hold-open and opening times were examined in quiescent environment, the evidence provided and discussed in this thesis implies that the door hold-open time has a clear effect and that the opening speed does not have a substantial effect on the air volume exchange through a doorway, at least with the hold-open times (2-25 s) and opening velocities (10-30 deg/s) examined here. However, more research is needed on this topic, especially with realistic ventilation rates to address their effect on the air volume exchange with different door opening times/speeds.

4.2.3 Occupant movement

Occupant movement induced flow field is a complex, dynamic and turbulent mixing problem which has been studied extensively and in detail in several studies (Okamoto and Sunabashiri, 1992; Bjørn et al., 1997; Matsumoto and Ohba, 2004; Edge et al., 2005; Choi and Edwards, 2008, 2012; Hathway et al. 2011; Poussou and Plesniak, 2012, 2015; Wu and Gao, 2014; Hang et al., 2014; Wu and Lin, 2015; Tao et al., 2017, 2018, 2020; Bhattacharya et al., 2020 A). In general, a moving body can induce substantial airflows in indoor environments and create a notable wake behind a moving body in which air can be dragged over notable distances. Although effect of various aspects, like limbs pendulum, body shape, wake etc. on human movement induced flows have been investigated previously, not many have examined the occupant movement generated air volume exchange through a doorway.

For instance, Tang et al. (2006) have previously assessed the wake flow rate to be around 0.08-0.23 m³/s. Eames et al. (2009) estimated that it can be up to 0.4 m³/s. The door hold-open time used in this study (in connection with passage) would then lead to several cubic meters of air flowing through the doorway induced by the passage. However, in this thesis the effect of passage on the air volume migration through the doorway was found to be between 0.24 m³ and 0.25 m³ for sliding and hinged doors respectively (Publication IV) with 12 ACH ventilation rate applied (with 3 s, 8 s and 5.4 s door opening, hold-open and closing time respectively). On the other hand, estimations based on Hayden et al. (1998) data show that in their case the air volume migration induced by a manikin movement was 0.34 m³ and 0.81 m³ for hinged and sliding doors respectively. Shaw (1976) measured that a fast walk of real person caused 0.29 m³ air volume transport from a treatment room to an air lock and that it was reduced to 0.08 m³ when the walk was slow (he did not specify the speeds of fast and slow walk).
There are several reasons for the simplified theoretical estimations of Tang et al. (2006) and Eames et al. (2009) to fail in their assessment compared to the measured ones: the estimated drag coefficient of the human body (~1) might be different or the flow rate might die out faster than expected. For instance, the CFD simulations in publications II and III show that the wake induced flow rate across doorway can actually reach values estimated by Tang et al. (2006) and Eames et al. (2009). However, this happens only momentarily immediately after the manikin has gone through the doorway and that flow rate reduces drastically after a few seconds.

The combined contribution of the door opening and occupant movement induced flows on the air volume exchange with hinged and sliding doors is also unclear. One of the very few studies directly looking at the differences between hinged and sliding doors experimentally (including movement through the doorway) was Hayden et al. (1998). Their tracer gas measurements showed that a manikin passage (simulating human movement) increased considerably the air volume migration through the doorway (especially with the sliding door), but that there was no clear difference in the results between the hinged and sliding doors (when the manikin passage was involved). However, the results of this thesis imply that there is a significant difference between hinged and sliding doors even when passage is involved, i.e. the sliding door opening and manikin passage generated substantially smaller air volume exchange than the hinged door. This was observed both with and without ventilation in use. These results are also supported by the findings of Tang et al. (2013), whose qualitative small-scale water model visualizations show similar behavior.

Occupant movement direction can also affect the air volume exchange through doorways. In Publication I it was found that the manikin passage direction had a notable effect on the air volume migration with the hinged door when ventilation was not on. However, when ventilation was applied (Publication IV), the passage direction appeared to have only a slight effect. It seemed like the high ventilation rates used in Publication IV (also typically used in isolation rooms) were able to cancel out any effect of the manikin passage direction with the hinged door (no clear dependence of the passage direction was seen with sliding door with or without ventilation applied). Also, Hayden et al. (1998) or Kokkonen et al. (2014) did not report any substantial effect of the occupant movement direction on the air volume transfer through the isolation room doorway when realistic ventilation rates were used.

One might argue that the static (i.e. no limbs movement included) and unheated manikin used in this thesis might affect the results. It is true that the human movement was simulated with a simplified manikin. However, it can be also argued that body heat and limbs movement should have only a small impact on the results. For instance, Wu and Gao (2014) examined the effect of body motion generated wake on the contaminant spreading with and without thermal plume by means of CFD simulations. They concluded that the effect of thermal plume on the wake flow was small with moving speeds above 0.4 m/s (in this thesis the manikin was moving with 1 m/s). Additionally, Han et al. (2015) has estimated that body motion has greater effect on the induced airflows than
swinging arms and legs. These results imply that the missing body heat and limbs pendulum should not affect the results of this thesis notably.

Overall, it appears that the effect of passage is notable but not the dominating factor with hinged doors but has a slightly larger effect with sliding doors; at least in hospital environments where wide doors are typically used for easy access with patient beds or with wheelchairs.

4.2.4 Temperature difference

As discussed previously, it looks like the door hold-open time has a notable effect on the air volume exchange across a doorway induced by the door opening. However, it can be quickly surpassed by other effects like temperature difference (density difference) driven flow, especially if the door is kept open for extended periods. The effect of temperature difference on the heat and mass transfer through rectangular openings in static conditions have been studied and discussed extensively previously by others (Brown and Solvasson, 1962; Lidwell, 1977; Kiel and Wilson, 1989; van der Maas (Ed.), 1992; Etheridge and Sandberg, 1996; and references therein just to name a few). The role of two-way airflow due to temperature difference has also been established in disease transmission previously (Chen et al., 2010; Hang et al., 2015). However, the effects of dynamic events such as door opening motion or passage are not well examined in this context.

The findings of this study (in Publication I) indicate that the effect of temperature difference driven flow is more notable for the sliding door than for the hinged door. The strong flow induced by the opening action of the hinged door can delay the onset of the temperature difference driven airflows across the doorway at the beginning of the door opening phase. Only after the initial impulse generated by the hinged door motion itself declines, the temperature difference starts to impact the air exchange between the rooms. The opening motion induced flows were significantly weaker, and the temperature difference driven flow started to dominate early on with the sliding door as indicated by the CFD simulations in publication III.

There seems to be no clear consensus whether the temperature difference driven or the door opening motion induced flow governs the exchange flows through the doorway with small temperature differences and short door cycle times. For instance, Shaw (1976) examined the air volume exchange across a doorway generated by hinged and sliding doors with temperature differences between 0-10 °C. He concluded that “temperature difference between adjacent rooms has a little or no effect on the amount of air transferred by a swing door” and that with the sliding door “the air movement is influenced markedly by temperature difference.” He also inferred that the negligible effect of the temperature difference on the swing door opening generated air volume transfer was due to the door pumping action overriding the buoyancy driven flow.

On the other hand, Kiel and Wilson (1989) carried out experiments in a full size test house and in a small-scale water model and concluded that already with temperature differences between 3 and 5 °C the door pumping induced effects
(with a hinged door) can be considered negligible as the buoyancy driven flows dominate air volume exchange.

More recently Lee et al. (2016) studied the interzonal exchange volume by means of CFD simulations and developed a regression model through which the effect of the temperature difference and door cycle time on the air volume exchange across a doorway can be calculated. According to their formula, the door pumping effect of a hinged door (with a total cycle time of 8 s) makes up 50% of the air volume exchange across the doorway with 5°C temperature difference between the rooms and hence it (the door pumping effect) should not be considered negligible. Unfortunately, Lee et al. (2016) did not take into account the occupant movement through the doorway which might have had a significant effect on the results, especially with small temperature differences.

The results of this study imply that although it is not clear when the temperature difference driven flows start to dominate, it appears that with hinged doors the door opening induced flows govern the flow phenomena across the doorway with small temperature differences (and with relatively short door opening times). On the other hand, already a small temperature difference can induce a continuous two-way air exchange across the open doorway with the sliding door and substantially increase the total air volume migration during door opening compared to the hinged door. The effect temperature difference becomes increasingly important when the door hold-open time increases.

4.2.5 Effect of ventilation

The effect of ventilation on the air volume exchange through the doorway was examined in Publication IV. Although increasing the ventilation rate generally accelerates the dilution of airborne contaminant concentrations and hence improve containment as less contaminants are present in the room and available for escape, ventilation can also increase air volume migration through an open doorway due to increased mixing and turbulence at the doorway (Lidwell, 1977). However, according to the results of this study, the examined ventilation rates did not affect notably the air volume exchange through the doorway, at least during the hinged door opening. Some variance was seen with the sliding door though. Especially 12 ACH ventilation rate was seen to increase the air volume exchange notably (with the sliding door).

Based on the findings of this study it appeared that the hinged door opening itself induced substantial mixing in the doorway which dominated or at least delayed the onset of the ventilation generated effects. For the sliding door this appeared not to be the case as the door motion generated airflows in the doorway seemed to be rather modest, as illustrated by the smoke visualizations. Hence, the onset of the ventilation induced mixing across the doorway was estimated not to be severely delayed by the sliding door opening motion. Thus, the ventilation can result in an increased air volume exchange through the doorway with sliding door, which was seen in the tracer gas measurements with 12 ACH.

Another ventilation related parameter possibly affecting the doorway airflows is the pressure difference (generated by the supply-exhaust flow rate differential) between the rooms. Although the pressure difference between the rooms
vanishes (and even reverses momentarily) when the connecting door is opened, it has been shown that it can still reduce the airborne contaminant transport across the doorway. For example, Adams et al. (2011), Mousavi and Grosskopf (2016) and Bhattacharya et al. (2020 B) have shown that increasing negative pressure differentials between clean and dirty zones can reduce aerosol escape through the doorway from a dirty area.

However, as mentioned above, the pressure difference vanishes between two rooms when the door connecting them is opened. Then only the imbalance of the supply-exhaust flow rate differentials between the rooms is left effective. That is the imbalance creates a net flow (directional airflow) through the open doorway towards the room with excess exhaust. Hence, one should also discuss the effect of supply-exhaust flow rate differentials or the net flow when talking about the effect of pressure differential on the airflows across doorways. In Publication IV of this thesis the supply-exhaust flow rate differentials (18-25 L/s) were found to reduce the door opening generated air volume exchange through the doorway with both door types (hinged and sliding). Although it is much more common to discuss the effect of pressure differentials, there are some studies in which the effect of flow rate differentials (directional air flow/net flow through the doorway) on the air volume exchange induced by the door opening and human movement through the doorway has been estimated or measured. For example, Shaw (1976) found that 0.30 m$^3$/s excess flow (i.e. 0.16 m/s face velocity in the doorway) for a sliding door (with 1 °C temperature difference across the doorway) would be needed to reduce the transfer close to zero. Hayden et al. (1998) estimated that flow rate differentials of c. 0.36 m$^3$/s and c. 0.26 m$^3$/s (0.17 m/s and 0.12 m/s face velocity in the doorway), with hinged and sliding doors respectively, would be enough to reduce the air volume migration through the doorway close to zero.

Based on the data of this thesis (Publication IV) it can be assessed that about 0.13 m$^3$/s and 0.06 m$^3$/s flow rate differential towards the isolation room (for the hinged and sliding doors respectively) would be needed to reduce the air volume migration out of the isolation room to zero. The results seem quite low compare to the results gained in the other studies. It should be noted that the estimations shown above, were only rough assessments and was based on linear extrapolation of a limited data set that did not consider the effects of passage, temperature difference and other disturbing effects typically present. Hence it was decided that the effect of higher directional air flow (net flow) on the air volume exchange across the doorway induced by the door opening, occupant movement and temperature difference should be investigated more thoroughly. This was done in Publication V.

### 4.2.6 Enhanced directional airflow

Like discussed above, even relatively small supply-exhaust flow rate differentials (directional airflow/net flow) appeared to reduce the level of containment failures (i.e. air volume exchange through the doorway) induced by door openings. On the other hand, higher flow rate differentials could drastically reduce
or even completely block the airflow (and hence airborne contaminants of flow-ing) out of the contaminant containing room.

In this thesis (in Publication V) effects of two different directional airflow rates (90 L/s and 190 L/s) on an air volume escape out of an isolation room induced by a hinged door opening were examined. According to the results, both directional airflow rates reduced the escaping air volume substantially.

Estimating the required directional airflow rate that would reduce the air migration close to zero is not explicit. For instance, further examination of the 90 L/s and 190 L/s cases without temperature difference shows, based on linear extrapolation of the results, that 0.30 m³/s (0.13 m/s face velocity) airflow is needed to reduce the air transfer by 99% compared to the reference case (without directional airflow). On the other hand, fitting and extrapolating an exponential curve to the same results shows that about 0.92 m³/s (0.41 m/s) directional airflow is needed for the 99% reduction. Of the two methods, the exponential function has a higher R²-value and hence could be argued to produce more accurate results in predicting the required flow rate value. The exponential function indicates that very high flow rates are required to reduce the air volume migration close to zero, if the function is accurate.

This thesis extended the scope of experimentally tested values of Shaw (1976) and Hayden et al. (1998) to higher directional airflow (net flow) values but like discussed in the end of the previous section (4.2.5 Effect of ventilation), there seems to be only very limited amount of published experimental measurement data investigating the dynamic effects of door opening motion and occupant movement induced airflows on the air transfer across the doorway with a substantial directional airflow, against which the results obtained here could be compared. However, a recent study by Shao et al. (2020) has investigated the effect of directional airflow across a cleanroom doorway in reducing a hinged door opening and manikin movement induced particle transmission into a cleanroom. They examined the effect of 210, 400 and 580 L/s airflow through the doorway with two walking speeds of a manikin passing through the doorway, thus extending the scope of the examined directional airflow rates to even higher values. They found that 400 L/s and 580 L/s directional airflow reduced the door opening and manikin motion generated particle transmission to the cleanroom notably compared to the 210 L/s case. However, even with the 400 L/s and 580 L/s airflow rates some particle transmission was observed. Unfortunately, they did not provide an estimate of the required doorway airflow rates to reduce the particle transport close to zero (or by 99%) and hence their results are difficult to compare against the results provided in this thesis. Nevertheless, they concluded that the reduction is not linear but more like polynomial or power function in relation to the directional airflow.

Lately also Wang et al. (2019) have investigated (through CFD simulations) the effect of reduced operating room exhaust airflow (creating an enhanced directional airflow out of the positive pressure OR) on preventing the bacteria carrying particles entering the OR during a sliding door opening. They found that a 20-30% reduction in the OR exhaust flow rate (i.e. about 400-600 L/s directional airflow through the OR doorway) resulted in a substantial decrease of
bacteria carrying particles in the OR. However, it should be noted that they carried out their simulations without human movement, which might affect the results and increase the intrusion of bacteria carrying particles to the OR.

On the other hand, according to Health Technical Memorandum 03-01 (2007) 390 L/s (c. 0.24 m/s) directional airflow is required across an open doorway (with 0.80 m x 2.01 m sized door) between clean and dirty environments to prevent most of the leakage and that 470 L/s (c. 0.29 m/s) flow rate is recommended between sterile and dirty areas to reduce the airborne contaminant transfer to zero. However, it is not clear whether the directional airflow rates specified in Health Technical Memorandum 03-01 (2007) take into account the door motion and occupant movement generated effects or not.

Although there is no clear consensus how high directional airflow rates are required to reduce the air volume transfer across the doorway to zero (or close to zero) in dynamic scenarios involving realistic door opening and occupant movement, this thesis shows that even with 190 L/s directional airflow a substantial reduction can be achieved. Here the level of directional airflow rate was limited to flow rates are typically readily available under normal isolation room operating conditions (~200 L/s). Utilizing readily available flow rates one avoids the need to increase fan speed during the door opening to create the enhanced directional airflow (net flow), which might take some time (especially with high additional flow rates). Also, it could be challenging to size/dimension the ducting, supply air terminal etc. to perform optimally with a very large airflow rate range. Hence, it was decided to limit the examined airflow rates to less than 200 L/s.

Another method utilizing readily available airflow rates to create directional airflow through a doorway is a positive pressure ventilated lobby (PPVL), which is described in Health Building Note 04-01 Supplement 1 (2013). In PPVL all supply air is supplied to the anteroom (no exhaust at the anteroom) from where it is directed to the isolation room (no supply in the isolation room) through a pressure stabilizer above the doorway. Then, when the door opens, the pressure stabilizer closes and all the air flows through the open doorway towards the isolation room. After the door has closed, the pressure stabilizer opens and the air flows through it from the anteroom to the isolation room.

PPVL seems like interesting method although there is only very limited amount of published data available about its performance regarding doorway exchange flows, especially during transient effects like door opening and occupant movement. Additionally, having a supply air terminal also in the isolation room (absent in PPVL) and utilizing it when the doors are closed can give more flexibility to the supply air distribution design which can have a notable effect on contaminant spreading, draught risk and thermal comfort inside the rooms (Qian et al., 2008; Berlanga et al., 2018; Kalliomäki et al., 2020).

Also supply air distribution in anterooms can affect notably the effectiveness of the directional airflow method. For example, supplying the air downwards above the doorway in an air curtain like manner might increase the effectiveness of the directional airflow and hence reduce the air transfer across the doorway. Only a basic overhead mixing ventilation was examined in this study and clearly
more research is needed to find an optimal supply air distribution solution to minimize the air escape through the doorway from the isolation room in combination with enhanced directional airflow.

4.2.7 Use of anterooms

In hospitals, one way to prevent the isolation room air from spreading directly to corridor is using an anteroom between the spaces. In general, anterooms can capture and dilute airborne contaminants escaping the isolation room through the doorway. Thus the anterooms can act as an effective isolation barrier between the dirty and clean zones. Additionally, they can serve as a place for HCWs to put on and take off PPE’s before entering and after leaving an isolation room.

Although anterooms are recognized as an integral part of infection control and hospital design (Subhas et al., 2013; ANSI/ASHRAE/ASHE Standard 170-2017) they don’t always provide absolute protection against containment failures. For example, Hang et al. (2015) have shown that a hinged door opening motion can lead to contaminant transport between isolation rooms connected by a shared anteroom. Also, Kokkonen et al. (2014) have concluded that “although an anteroom reduces leakage of infectious agents to the corridor significantly, it does not prevent this completely when HCWs move between the AIIR and corridor.”

Additionally, the size of the anteroom might affect its effectiveness in catching the escaped contaminants. However, there appears to be no clear evidence how the room sizes affect the door motion induced flows and air volume migration through the doorway though. For instance, Hayden et al. (1998) considered that a small anteroom might reduce and a large one increase the air volume migration to corridor. On the other hand, Kiel and Wilson (1989) found out that the air exchange volume across an outer door of a small test house was not substantially influenced by the room size or layout. Although the effect of the room size on the air volume exchange induced by the door opening and occupant movement were not explicitly examined in this thesis, the exchange was slightly smaller with a smaller anteroom (Publication V) compared to results with larger rooms (Publication IV). However, it is difficult to distinguish the true effect of the room sizes from the other factors involved. It appears that more detailed studies are needed in order to define the effect of the room sizes explicitly.

4.3 Practical implications

This study originated from an urge to minimize potential containment failures of isolation rooms generated by door openings and subsequent occupant movement through the doorways. This thesis provides new, profound and useful insights to the door opening related air volume exchange and airflow patterns through doorways. The information can be used to raise the awareness of the healthcare workers that doors are potential containment failure locations and that door opening itself can contribute to this.
Results from this study might alter the way the hospital isolation rooms are designed and used. Although people always need to pass through doors or doorways to attend to the patients within isolation rooms, these results may reinforce the importance of e.g. sliding doors, ventilation solutions and antechambers to protect staff, other patients and visitors outside the isolation room.

Especially sliding doors were found to be effective in reducing airflow leakage through doorways as compared to hinged doors (which create more disturbance to the ambient air with their motion) and may become more the norm for such isolation rooms. However, it is acknowledged that transition to sliding doors might be challenging due to strict space demands, additional retrofitting costs etc. Nevertheless, the results of this study clearly highlight the benefits of the sliding doors and hence it is considered that they should be at least considered when constructing new hospitals or renovating old ones.

Also, optimal door opening parameters can be taken into use in hospitals to reduce the airborne contaminant transport out of the isolation room during door operation. Additionally, supply-exhaust flow rate differential (pressure difference), especially enhanced directional airflow across the doorway can reduce the amount of air escaping the isolation room and thus can alter their recommended values in guidelines and standards for reducing the degree of containment failures caused by a door opening.

Although the examined ventilation rates did not affect notably the air volume migration out of the isolation room generated by the hinged door opening, the role of ventilation in airborne transmission of infections in the built environment is evident (Li et al., 2007). However, there seems to be no clear consensus on the minimum ventilation requirements for hospital isolation rooms and hence typically mixing ventilation with sufficiently high air change rates (e.g. 6-12 ACH) are recommended (ASHRAE 170-2017; CDC, 2005; HTM 03-01 Part A, 2007; WHO, 2014). Yet, it should be noted that “air change rate should not be used as the sole indicator of the air delivery system’s ability to reduce exposure to airborne infectious droplets” as argued by Pantelic and Tham (2013). Nevertheless, increased ventilation can reduce the containment failures induced by the door opening and human movement as the concentration of airborne contaminants are quickly diluted already in an isolation room and hence less agents can be disseminated through the doorway to the adjacent spaces. In general, factors that reduce the door opening induced airflow across the doorway should be combined with high ventilation rates in order to guarantee optimal outcome when minimizing the airborne transmission of infections across the doorway.

Although the research of this thesis focused on the hospital environment context, the results can be applied to other environments, where reducing doorway exchange airflows generated by door opening, occupant movement, temperature difference etc. are also important. For example, one application area could be cleanroom environments in electronic, food and pharmaceutical industry where product contamination might happen if dirty outside air is able to penetrate far into the room due to door opening and occupant movement.
4.4 Limitations of the study

In this study, some simplifications and assumptions were made. For instance, all the experiments carried out in this thesis were done in a laboratory, which can be considered to be more idealistic than real environments e.g. at hospitals. On the other hand, in laboratory settings one can usually control the study parameters more accurately and hence study the effect of different factors and parameters more explicitly. Additionally, patient rooms, especially isolation rooms, are typically constantly occupied, hence making it difficult to find available patient/isolation rooms in real hospital settings. Also, patient room designs (floor plan geometries) can vary and hence testing one of them might not produce representative/generalizable results.

One of the main limitations of this study was that the investigations covering research question 2 (How much the air exchange through the doorway can be reduced by optimal choice of door opening parameters?) were carried out only without ventilation applied (results of Publication I). Hence, these findings (e.g. the effect of door opening, hold-open and total cycle times on air volume exchange across the doorway) are applicable only in relatively quiescent environments with low ventilation rates and cannot be generally extended to encompass the hospital isolation room settings.

The tracer gas methods used in this study relied on full mixing of the room air. However, this might not be the case always and concentration changes are possible (especially during the door opening the local concentrations can change rapidly in the rooms). To reduce the possible concentration gradients and hence their effect on the results, several measures were applied: the measurements were repeated several times (3-12) for each tested case; the room air was mixed with fans (in Publications I-III) or with high ventilation rates (in Publications IV and V); a visual inspection of the smoke dispersal and concentration gradients were made, when recoding the smoke visualization videos, which showed quick and uniform distribution of the smoke inside the rooms. It is acknowledged that direct measurements to evaluate the effectiveness of the air distribution in the rooms would have been valuable (in Publications IV and V), not only to assess the impact on the tracer gas measurements but also to provide additional insights to ventilation effectiveness and to temporal and spatial infection risk – whether the peak or the cumulative load with time matters the most.

Another limitation related to the experimental tracer gas methods was that they did not provide information about the temporal evolution of the air volume exchange through the doorway. The methods provided only the total amount of air flowing through the doorway during the door opening. It would have been interesting to measure the exchange flow rate as a function of time in different cases, but it was considered to be impractical or even impossible with the measuring equipment available. However, the temporal evolution of the exchange flows was covered to some extent with the CFD simulations (in Publications II and III), which provided information about the exchange flow rates through the doorway for the hinged and sliding doors in the baseline cases without ventilation.
In this thesis the occupant movement through the doorway was simulated with mechanical motion of a static and unheated manikin. One could argue that more realistic results could have been achieved by simulating the movement with a real person. For instance, a real person might not open the door completely (i.e. 90° with the hinged door) as was done with the manikin. He/she might sort of sneak in and out of the room instead. However, this is not clear and can depend heavily e.g. on personal habits, activity type (entry/exit), and the direction a person is heading after the door opening.

Additionally, an automated door opener was used to open the door in this study. Although they are not yet utilized widely, they are used more and more everywhere, even in hospitals, and hence they might become the norm in everyday life at healthcare facilities in the future. Nevertheless, using a simplified and computer-controlled manikin movement and door opening sequence made the synchronization of the movements easier, more accurate and repeatable throughout the experiments in this thesis.

The total cycle time of the door used in this study (when combined with manikin movement) could be considered slightly long compared to scenarios encountered in real hospital environments. For example, Shaw (1976) investigated the door opening habits in real hospital settings and found the average door cycle time to be between 7-10 s. Usage of these shorter total cycle times would have probably led to smaller air volume migrations across the doorway than was measured in this study. However, the door total cycle time had to be set long enough to prevent the manikin from colliding with the door, which is a clear limitation of this study.

Another limitation of this study is that the effect of directional airflow was examined only with a hinged door. The decision was affected by several reasons, e.g. the observation that hinged doors are more common door type in hospital isolation rooms than sliding doors. Nevertheless, it is understood that excluding sliding doors when examining the effect of enhanced directional airflow through the doorway is a clear limitation of this thesis, as the escaping air volume through the doorway could have been reduced notably with sliding doors.

CFD simulations of the moving bodies (door and manikin) were carried out with the immersed solid method. This method is not ideal with passive scalar method in Ansys CFX (at least with the version that was used in this study). There was some leakage through the moving bodies which may have introduced some error to the simulation results. Additionally, the manikin model in the simulations was not identical with the one used in the experiments. In general, the error of the simulation results is expected to be small as the results were in line with the experimental investigations.

4.5 Recommendations for future research

This thesis provided systematic and comprehensive characterization of the air volume exchange and airflow patterns through the doorway generated by a door opening and a manikin movement. However, there are still many issues that should be studied in the future.
The experiments were carried out in a laboratory environment and the occupant movement was simulated with a moving manikin for less complexity and to be able to repeat the door opening and occupant movement accurately and systematically. For enhanced realism, it would be necessary to carry out the experiments with real human movement and door opening. In general, the solutions of this study (sliding doors and directional air flow) should be examined also in real hospital settings to test their effect in practice.

One factor which plays essential role in transport of airborne contaminants is supply air distribution. In hospital isolation rooms, supply air distribution can reduce HCW exposure to the patient exhaled contaminants notably (Qian et al., 2008; Berlanga et al., 2018; Kalliomäki et al., 2020). It is expected that supply air distribution and room airflow patterns are also relevant in limiting airborne contaminant transport through doorways and hence between different zones. For instance, Wang et al. (2019) noted that for more accurate assessment of the impact of door openings on the risk of surgical site infections (SSIs) in ORs, also the dispersion of the penetrated contaminants inside the OR needs to be taken into account in addition to the air volume transfer through the doorway. Hence it is considered important to examine the effect of different supply air distributions on the exchange flows through doorways induced by door openings.

One topic for further research related to supply air distribution and room flow patterns could be air curtains. Air curtains have been found beneficial in different industrial and commercial environments with high traffic (e.g. in cold storages, building entrances etc.) for aerodynamic sealing of spaces (or at least for limiting heat and mass transfer through large openings). However, the effectiveness of air curtains in reducing airborne contaminant transport through a doorway induced by transient effects like door opening and occupant movement is not well established and characterized in hospital environments.
5. Conclusions

In healthcare settings, patients with airborne infections are typically placed in negative pressure isolation rooms to reduce the spreading of the infections. Nevertheless, containment failures can still happen, and it has been estimated that the opening of doors and subsequent occupant movement through the doorway are among the most relevant factors causing transient breakdown of airborne isolation conditions in hospital isolation rooms. However, it is still not well-established what factors govern the airflows through the doorways during the door opening and occupant movement. For instance, can the air exchange through the doorway be reduced by optimal choice of door opening parameters? How effective is directional airflow in reducing the exchange flows? What is the effect of occupant movement through the doorways? What are the differences between hinged and sliding doors?

In this thesis the air volume exchange and airflow patterns through a doorway induced by a door opening motion and occupant movement were examined in order to provide answers to the above-mentioned questions. For example, the effect of several different door opening parameters on the hinged and sliding door opening motion induced exchange flows across the doorway were studied extensively in Publications I-III. On the other hand, the effects of ventilation related parameters on the doorway exchange flows induced by the hinged and sliding doors were covered in Publication IV. In addition, the effect of enhanced directional airflow (net flow) on the exchange airflows across the doorway was examined in Publication V.

The exchange airflows through doorways induced by door opening and occupant movement were examined with experimental methods (in Publications I, IV and V) and with CFD simulation methods (in Publications II and III). All the experiments carried out in this study were performed in a controlled laboratory environment. The laboratory experiments consisted of tracer gas measurements and smoke visualizations, which were used to measure the air volume migration across the doorway and to illustrate the airflow patterns. In addition to the experimental methods, CFD simulations were performed as well. The simulations were used to further examine the flow phenomena and the temporal evolution of the air volume exchange and the flow patterns.

The results show that the door opening generated a notable air volume exchange across the doorway (0.27-2.42 m³ depending on the examined case). The clearest factors were the door type, the manikin movement through the doorway, door hold-open time, temperature difference and the enhanced directional
Conclusions

One of the most important findings of this study was that the opening of the sliding door typically induced notably smaller air volume migration across the doorway than the hinged door. That is, the air volume exchange was found to vary between 0.29-1.13 m³ with the sliding door and between 1.16-2.42 m³ with the hinged door (depending of the examined case). Hence, the reduction of the air volume migration with the sliding door varied between 36-79% compared to the hinged door induced exchange (except when temperature difference was present).

Also, an important finding of this study was that the directional airflow (net flow) across the doorway reduced the air volume migration substantially. Two different directional airflow rates were examined in this thesis, i.e. 90 L/s and 190 L/s (the experiments were carried out only for the hinged door). The air volume migration through the doorway was found to be 0.80 m³ and 0.51 m³ with 90 L/s and 190 L/s directional airflow rates respectively. That is, the reduction being 38% (0.49 m³) and 60% (0.78 m³) with the 90 L/s and 190 L/s directional airflow (net flow) rates respectively, compared to the reference case without directional airflow (which induced an air volume exchange of 1.29 m³). The directional airflows were also effective in decreasing the air volume exchange when there was a temperature difference between the rooms, although the relative effectiveness was slightly reduced compared to the isothermal conditions.

Even a small temperature difference between two rooms can increase the air volume transfer through the doorway notably. In this study it was found that 2 °C temperature difference increased the air volume transfer induced by the hinged and sliding door opening with 41% and 304% (i.e. from 1.39 m³ to 1.96 m³ and from 0.56 m³ to 2.26 m³) respectively. Hence, attention should be paid to maintain isothermal conditions between adjacent spaces to mitigate the contaminant spreading through the doorway during door opening.

Additionally, occupant movement was also found to increase the exchange flows notably. A manikin simulated motion appeared to have a distinctive effect on the airflow patterns and air volume migration across the doorway, especially with the sliding door. The exchange volume induced by the manikin movement varied between 0.23-0.36 m³ depending on the case parameters.

Also, the door hold-open time affected the air volume migration through the doorway. It turned out that the longer the hold-open time the greater the air volume exchange across the doorway. On the other hand, the door opening time (i.e. speed) was not found to affect the air volume transfer notably (after the effect of total cycle time was removed from the results). Hence, to minimize the effect of the hold-open time the door cycle should be as short as possible. Although the effects of the door opening speed and hold-open time parameters were tested only in quiescent environment without ventilation in use, they provided valuable information about the nature and baseline effects on the exchange flows.

Ventilation rate did not appear to affect the air volume transfer across the doorway generated by the door opening notably, although there was some variance in the results with the sliding door. Nevertheless, the room ventilation
plays an important role in the mitigation of exposure to airborne contaminants in general. That is, the higher the ventilation flow rate, the quicker the dilution, the lower the contaminant concentration and hence also the lower the exposure (assuming effective mixing in the space).

CFD simulations provided additional and detailed information about the air volume exchange and airflow patterns through the doorway induced by the door opening motion, manikin movement and temperature differences. The simulations proved to be capable of modelling the airflows well and accurately. They were especially useful for investigating the time evolution of the exchange flows, particularly the air volume migration flow rate.

In summary, the findings of this thesis highlight the importance of the sliding doors and effective directional airflow in reducing exchange airflows through doorways induced by door opening motion and occupant movement. Additionally, the results imply that temperature differences between spaces should be avoided in order to mitigate the dispersion of the airborne contaminants through the doorway. Even though utilization of sliding doors and directional airflows might not be directly feasible in old buildings, the installations should be at least considered when constructing new hospitals or remodeling the old ones.
References


Ai, Z., Mak, C.M., Gao, N. and Niu, J. (2020). Tracer gas is a suitable surrogate of exhaled droplet nuclei for studying airborne transmission in the built environment. Building Simulation, 13 (3), 489-496.


Fontana, L. and Quintino, A. (2014). Experimental analysis of the transport of airborne contaminants between adjacent rooms at different pressure due to the door opening. Building and Environment, 81, 81-91.


http://dx.doi.org/10.1080/23744731.2016.1155959.


References

Tao, Y., Inthavong, K., Petersen, P., Mohanarangam, K., Yang, W. and Tu, J. (2020). Vortex structures and wake flow analysis from moving manikin models. Indoor and Built Environment, 0 (0), 1-16, DOI: 10.1177/1420326X19893013.


