Investigations of Flow Patterns in Ventilated Rooms Using Particle Image Velocimetry

Applications in a Scaled Room with Rapidly Varying Inflow and over a Wall-Mounted Radiator

by

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Abstract

This thesis introduces and describes a new experimental setup for examining the effects of pulsating inflow to a ventilated enclosure. The study aimed to test the hypothesis that a pulsating inflow has potential to improve ventilation quality by reducing the stagnation zones through enhanced mixing. The experimental setup, which was a small-scale, two-dimensional (2D), water-filled room model, was successfully designed and manufactured to be able to capture two-dimensional velocity vectors of the entire field using Particle Image Velocimetry (PIV). Using in-house software, it was possible to conclude that for an increase in pulsation frequency or alternatively in the flow rate, the stagnation zones were reduced in size, the distribution of vortices became more homogeneous over the considered domain, and the number of vortices in all scales had increased. Considering the occupied region, the stagnation zones were moved away in a favorable direction from a mixing point of view. In addition, statistical analysis unveiled that in the far-field occupied region of the room model, stronger eddies were developed that we could expect to give rise to improved mixing. As a fundamental experimental study performed in a 2D, small-scale room model with water as operating fluid, we can logically conclude that the positive effect of enhanced mixing through increasing the flow rate could equally be accomplished through applying a pulsating inflow.

In addition, this thesis introduces and describes an experimental setup for study of air flow over a wall-mounted radiator in a mockup of a real room, which has been successfully designed and manufactured. In this experimental study, the airflow over an electric radiator without forced convection, a common room-heating technique, was measured and visualized using the 2D PIV technique. Surface blackening due to particle deposition calls for monitoring in detail the local climate over a heating radiator. One mechanism causing particle deposition is turbophoresis, which occurs when the flow is turbulent. Because turbulence plays a role in particle deposition, it is important to identify where the laminar flow over radiator becomes turbulent. The results from several visualization techniques and PIV measurements indicated that for a room with typical radiator heating, the flow over the radiator became agitated after a dimensionless length, 5.0–6.25, based on the radiator thickness.

Surface properties are among the influencing factors in particle deposition; therefore, the geometrical properties of different finishing techniques were investigated experimentally using a structured light 3D scanner that revealed differences in roughness among different surface finishing techniques. To investigate the resistance to airflow along the surface and the turbulence generated by the surfaces, we recorded the boundary layer flow over the surfaces in a special flow rig, which revealed that the types of surface finishing methods differed very little in their resistance and therefore their influence on the deposition velocity is probably small.

Keywords: Particle Image Velocimetry (PIV), experimental study, structured light 3D scanning system, ventilation, varying flow rate, room model, wall-mounted radiator, air, water, flow

Sammanfattning

Det övergripande syftet med den första studien i avhandlingen var att undersöka hypotesen att ett pulserande inflöde till ett ventilerade utrymme har en potential till att förbättra ventilationens kvalitet genom att minska stagnationszoner och därigenom öka omblandningen. För genomförande av studien byggdes en experimentuppställning i form av en tvådimensionell (2D) småskalig modell av ett ventilerat rum. Strömningsmediet i modellen var vatten. Det tvådimensionella hastighetsfältet registrerades över hela modellen med hjälp av Particle Image Velocimetry (PIV). Vid ett stationärt tillflöde bildas ett stagnationsområde i centrum av rumsmodellen. Vid ett pulserade inflöde genererades sekundära virvlar. Med en egen utvecklad programvara var det möjligt att kvantifiera statistiken hos virvlarna. Det pulserade inflödet gjorde att inom området där det vid stationärt tillflöde fanns en stagnationszon ökade antalet virvlar i alla storlekar och fördelningen av virvlar blev mera homogen än tidigare. Detta kan förväntas ge upphov till förbättrad omblandning. Baserat på en grundläggande experimentell studie utförd i en småskalig tvådimensionell rumsmodell med vatten som strömningsmedium kan vi logiskt dra slutsatsen att ett pulserande tilluftsflöde har en potential att förbättra omblandningen.

I en fortsatt studie i avhandlingen visuliserades och mättes hastighetsfältet och därefter beräknades statistiska värden av exempelvis medelhastighet, standardavvikelse och skjuvspänning hos hastighetsfluktuationerna i luftströmmen över en väggmonterad radiator med 2D-PIV-teknik. Bakgrunden till studien är att en bidragande orsak till partikelavsättning på väggytor är turbofores som uppträder vid en turbulent luftström. Studien genomfördes genom uppbyggnad av en fullskalig rumsmodell. Eftersom turbulens spelar en roll vid partikelavsättning genom turbofores är det viktigt att identifiera var det laminära flödet över radiatorn blir turbulent. Resultaten baserat på visualisering och PIV-mätningar indikerade att, för ett rum med denna typ av radiatoruppvärmning, blev flödet över radiatorn turbulent efter en dimensionslös längd lika med 5,0–6,25 gånger radiatorns tjocklek.

Ytors egenskaper är viktiga vid partikelavsättning. Därför har de geometriska egenskaperna hos några olika metoder för ytbehandling undersökts experimentellt med hjälp av en scanner för strukturerat 3D-ljus. Resultaten visar på skillnader i ytråhet hos de olika ytbehandlingsmetoderna. För att undersöka motståndet mot luftströmning längs ytan och den turbulens som genereras av ytorna registrerade vi gränsskiktsflödet över ytorna i en speciell luftströmningsrigg. Detta påvisade att motståndet hos de olika typerna av ytbehandlingsmetoder skilde sig mycket litet åt och därför är troligt vid deras påverkan på depositionshastigheten mycket liten.

Nyckelord: Particle Image Velocimetry (PIV), experimentell studie, scanningsystem för strukturerat 3D-ljus, ventilation, varierande tilluftsflöde, rumsmodell, väggmonterad radiator

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1. Objectives of the Work

An overarching goal of this thesis was to investigate the whole field flow patterns of various flows in an indoor environment using a scaled model and full-scale mockup and different operating fluids in conjunction with Particle Image Velocimetry. The starting point of this work was research to develop a new air distribution principle, based on supplying rapidly varying ventilation flow rates to an enclosure. The main goal was to perform fundamental experimental studies of the new air distribution principle using PIV. The objectives included a literature review of jets – their behavior, characteristics, types, and so on –, development of a new water-operated, small-scale 2D room model and a water circulation loop suitable for PIV experimentations, video visualization studies to find PIV measurements' flow rates and pulsation frequencies, and PIV measurements of the effect of pulsating inflow to the room model. Previous studies have shown that applying a pulsating inflow generated secondary vortices, which could improve air distribution efficiency. For this study, the conditions for generating the secondary vortices and their characteristics could be quantified using an in-house computer program. Moreover, the flow could be visualized with the aid of acquired measurement data from PIV, using constant or pulsating inflow, and other important flow characteristics could be analyzed and compared using in-house software for important regions in the scaled room.

Three articles resulted from this stage of the research:

- PIV visualization study in a two-dimensional room model with rapid time varying ventilation flow rates (conference paper, 2011)
- PIV study of ventilation quality in certain occupied regions of a two-dimensional room model with rapidly varying flow rates (journal paper, 2013)
- Experimental study on the effect of pulsating inflow to an enclosure for improved mixing (journal paper, 2013)

My thesis work continued within the framework of another research program in which PIV technology was a useful tool: the Swedish Energy Agency's "Save and Preserve" (*Spara och bevara*) program, which seeks ways to save energy in historic buildings while preserving historical and aesthetical values. In historic buildings, conflict may arise between indoor climate for people and preservation of artifacts. Within this project's framework, studies were conducted regarding parameters important for particle deposition that result in surface blackening. The work included both studies of surface structures and measurement of airflow over a wall-mounted radiator with the goal of conducting fluid flow/surface structure experiments on the process of surface blackening. As a first objective, a thorough literature review provided necessary knowledge into surface blackening, particle deposition, and aerosol science and technology. After the study phase, I designed and developed a full-scale room to conduct detailed high-quality PIV measurements of air flow over a wall-mounted radiator and to perform video visualization of the air flow over the wall-mounted radiator. In addition, I analyzed and processed PIV measurement data of the air flow over the radiator using in-house software. Moreover, the geometrical micro-surface profiles of different surfaces were measured using structured light 3D scanning system and quantified and analyzed using the related software.

Three articles resulted from this stage of the research:

- Plaster finishes in historical buildings – Measurements of surface structure, roughness parameters and air flow characteristics (conference paper, 2013)
- Particle image velocimetry (PIV) visualization of air flow over a wall-mounted radiator (conference paper, 2014)
- Particle image velocimetry visualization and measurement of air flow over a wall-mounted radiator (under revision by the author after being submitted for journal publication)

2. Background

Energy provides with comfort and mobility and is essential for prosperous industry and healthy, comfortable lifestyles. However, energy production (electricity and heat) and consumption (in households, industries, or for transportation) have a huge impact on the environment. Emission of greenhouse gases, exposure of air, soil, and water to pollutants, and waste generation are some examples of the long-term impacts of energy use on the environment. These impacts contribute to climate change, damage natural water and soil ecosystems, produce air pollution, and cause adverse effects to human beings' mental and physical health.

Energy supply security and environmental sustainability and competitiveness are central objectives of the EU's energy policy, reflected in proposals of the European Council for an Energy Policy for Europe (EEA, 2006). After long debates and discussions, the European Council adopted the EU climate and energy package in December 2008 (Council of the European Union, 2008), which the 27 heads of state and governments agreed to implement by 2020. As stated in the European Commission's Climate Action (2015), these "20-20-20 targets" include:

- cutting greenhouse gases by at least 20 percent of 1990 levels (30 percent if other developed countries commit to comparable cuts)

- cutting energy consumption by 20 percent of projected 2020 levels by improving energy efficiency, and increasing use of renewables (wind, solar, biomass, and so on) to 20 percent of total energy production

- reducing by 20 percent the emissions of greenhouse gases, increasing by 20 percent energy efficiency in the EU, and increasing renewables to 20 percent of total energy consumption in the EU

It is also stated in the package (European Commission, 2015) that for the building sector (households), emissions have to be cut to 10% below 2005 levels through binding national targets, with higher reduction targets for wealthier countries than for poorer ones.

To reach these targets in the building sector, a wide range of energy measures must be implemented to provide EU citizens with the most energy-efficient buildings. Heating, cooling, ventilation, and air conditioning are responsible for almost 40 percent of total energy consumption, with an expanding trend, and produce a considerable amount of CO2 emissions (Concerted Action EPBD, 2015; The European Parliament and the Council of the European Union, 2003).

In response to the EU's energy and emission regulation and targets for the building sector, Sweden established special regulations and issued new targets and action plans. Sweden's National Board of Housing, Building, and Planning (Boverket) issued special regulations to limit energy consumption for buildings, depending on location and type of heating (Boverket, 2008). The Boverket also issued secondary goals for the year 2020 regarding indoor environments, energy consumption, and sustainability in the building sector (Boverket, 2007).

In addition to meeting energy and environmental goals in heating, cooling, ventilation, and air conditioning, the building sector also must provide a healthy indoor environment for occupants. Nearly one million people in Sweden in 1999 had symptoms of illness related to deficiencies in the indoor environment, such as an inappropriate ventilation system (Boverket, 2007). Moreover, ultrafine particles from traffic, cooking, candle combustion, construction, and so on may penetrate buildings and pose a huge risk to both occupant health and building preservation (through deposit of dust and ultrafine particles, including micro and nanoparticles, onto building surfaces). Building air-tight, highly insulated structures to increase energy efficiency for decades has produced more problems with allergy, asthma, and Sick Building Syndrome (SBS) symptoms among occupants (Wargocki et al., 2000; Wargocki et al., 2002). According to Wargocki et al. (2000), increasing the ventilation rate decreases the percentage of occupants who are dissatisfied with the air quality, increases the perceived air freshness, and eases difficulty in thinking. A multidisciplinary group of European scientists with expertise in toxicology, medicine, epidemiology, and engineering conducted a large review study, EUROVEN, which showed that increasing the rate of outdoor air supply in built environments improved perceived air quality. In addition, Wargocki et al. (2002) found that outdoor air supply rates below 25 lit/s per person increased the risk of SBS symptoms and affected health and productivity. Other researchers found that although ventilation did not have a direct influence on occupants' health or perceptions, the ventilation rate influenced indoor environmental conditions such as air pollutant concentrations that did affect occupants' health and building preservation and maintenance costs (Airaksienen et al., 2007). Therefore, the ventilation rate is capable of modifying occupants' health or perceptions and preservation issues in buildings.

Two serious questions arise: (1) Do we really want to save energy at the expense of indoor climate quality and health? and, (2) Are there any possible measures to improve ventilation quality while saving energy, too? These issues and formulated questions call for research and development activities to develop novel heating, cooling, ventilation, and air conditioning techniques for higher energy efficiency, better ventilation efficiency, a healthier living standard, and minimized damage to buildings.

In this thesis, I present a novel solution that consumes less energy for ventilation without compromising occupants' health and that is introducing rapid variations to the inflow. In a series of experimental studies, I tested the hypothesis that a pulsating inflow has the potential to improve ventilation quality by reducing stagnation zones through enhanced mixing. Performed as fundamental experimental studies in a small-scale room model, the research produced results that point to the logical conclusion that the positive effect of enhanced mixing by increasing the flow rate could be accomplished equally by applying a pulsating inflow.

Another series of studies aimed at energy conservation, occupant health, and building preservation concerned research for the Swedish Energy Agency's (*Energimyndigheten*) "Save and Preserve" (*spara och bevara*) program. The research project goal is to find ways to save energy in historic buildings while preserving historical and aesthetical values. Soiling caused by particle deposition (related to thermophoresis, turbophoresis, and surface structure) may reduce aesthetical values and contribute to degradation of valuable objects. My focus for this part of the thesis was to investigate the flow over radiators (flow mapping) and measure surface structures. Again, PIV was used both for measuring the flow and to collect statistical data about the velocity variations.

3. Introduction

Flow visualization is the art and science of making flow patterns visible to us. Common fluids such as air and water are transparent, and their flow patterns are invisible without some special tool and methods. Flow visualization experiments began by simple measures such as spilling ink into water, and in response to scientific interest in fluid phenomena, several experimental tools and measurement techniques were developed. Flow visualization allowed the whole flow field to be observed in an instant, but whole field quantitative information about flow was missing. In the 20th century, fluid flow studies were aided by advanced imaging techniques and powerful computing tools, which made the quantitative measurement of whole flow fields possible through velocimetry of seeded flow in a fluid media, or so-called particle image velocimetry (PIV). As a response to scarcity of experimental knowledge in whole field studies of flow in ventilated enclosures, this thesis focuses on performing PIV experiments in ventilated regions using either full-scale or small-scale models.

One study category in which PIV flow visualization has been utilized is the application of rapid-time varying ventilation flow rates to an enclosure. The most common approach in air distribution in Swedish premises is mixing ventilation created by supply of a constant airflow rate with a mechanical ventilation system. This type of ventilation may cause problems such as draught, stagnation zones, and subsequently low ventilation efficiencies. These drawbacks call for experimental investigations of novel ventilation techniques.

Bajura and Szewczyk (1970) and Bajura and Catalano (1975) conducted early experimental studies on the application of transitions for a two-dimensional wall-jet. Previous studies (Sandberg and Elvsen, 2004; Wigö and Knez, 2005) showed that rapidly varying air inflow, as an alternative ventilation method, could reduce stagnation and increase efficiency of ventilation. Another study by Kandzia et al. (2011) indicated that unsteady inflow boundary conditions in a ventilation system could result in the need for lower mean velocity values for the inflow compared with a steady (constant rate) inflow. Airflow variations also have been studied from the perspective of thermal comfort (Hua et al., 2012; Huang et al., 2012; Xia et al., 2000). These results indicated that for a limited air velocity, variations of airflow could be considered as a control factor to compensate for increased temperature in warm environments.

Within chemical engineering, pulsating flow has been used as a means of enhancing the heat transfer rate (Keil and Baird, 1971). According to Keil and Baird, pulsating flow has been used since the 1930s as a heat-transfer boosting method, and strong oscillations of the flow were generated in experiments. In ventilation of occupied rooms, there is always a comfort constraint: The air motions generated may not create a sensation of draught for the occupants. Therefore, in contrast to the variations generated in chemical engineering applications, we chose a "milder" variation of the supply flow rate to study. The variations generate secondary vortices that are shed into the interior of the room. People's sensation of the variations, the eventual noise generation, and energy consumption must be explored in separate tests. As a first goal for this thesis, I performed whole field flow visualization experiments using PIV measurements in a series of fundamental studies on a ventilation system with rapidly varying supply flow rate using a small-scale, two-dimensional (2D) room model. With in-house software, vortices were quantified and information about the probability distributions of vortex size, strength, and location were obtained. Because the presence of vortices is a prerequisite for good mixing, this type of vortex analysis was important for quantifying the ventilation system's performance. Moreover, statistical analysis of the PIV measurements using in-house software and whole field measurement data were performed in the whole-room model domain and across certain occupied and upstream regions to compare the results of a rapidly varying inflow to a fixed mechanical inflow in the fluid distribution system.

Another area in which PIV has been utilized is the study of flow over a wall-mounted radiator. Radiators are commonly used in Scandinavian countries for heating. Airflow over a heated panel radiator is a decisive factor for air circulation in room ventilation studies and other related issues such as particle deposition on wall surfaces and energy efficiency. Relevant studies on heating radiators have mainly focused on the flow regime in the radiator-heated rooms (including CFD simulations), energy consumption and efficiency, heat output and transfer, novel radiator designs (such as convective or combined/cooling radiators), measures to improve performance, and comparison with other types of heating systems (Arslanturk and Ozguc, 2006; Baldinelli and Asdrubali, 2008; Beck et al., 2001, 2004; Gritzki et al., 2009, 2013; Hasan et al., 2009, Myhren and Holmberg, 2006, 2007a, 2007b, 2008, 2009, 2011, 2013; Sevilgen and Kilic, 2011; Shati et al., 2011; Ward, 1991). Few studies have looked at indoor air quality and thermal comfort for radiator-heated enclosures (such as Krzaczek and Tejchman, 2012; Myhren and Holmberg, 2006, 2008), although these are important factors for heating premises with occupants. Moreover, no real scale, quantitative, whole field, peer-reviewed study could be found.

Good air circulation is the key prerequisite to obtain desirable thermal comfort in a radiator-heated enclosure. A radiator generates a warm air stream that starts as a laminar flow; then gradual undulations are generated that ultimately transit to a turbulent flow. In a radiator-heated room, an air plume formed over the radiator mixes air and contributes to the room ventilation. The turbulent flow produces a higher degree of mixing than the laminar flow, and therefore, identifying where the laminar flow over the radiator becomes turbulent is important.

Surface blackening due to particle deposition is another factor that calls for monitoring the local climate over a heating radiator. Air turbulence near surfaces is an important driving mechanism for deposition of airborne particles onto surfaces. Soiling or surface blackening is often restricted to certain areas and occurs when air-borne particles are deposited on surfaces such as walls. In radiator-heated buildings, particle deposition often occurs in the vicinity of radiators. Obviously, a warm air stream striking a cold wall causes a temperature gradient that can result in thermophoresis, which involves particle transport downwards the temperature gradient. Turbophoresis is the transport of particles from a region of higher turbulence intensity towards a region of lower turbulence intensity (Guha, 1997, 2008). This transport mechanism of particles is attributed to the turbulent fluctuations of the particles. The gradient of the particles' velocity fluctuations gives rise to the turbophoretic velocity of the particles. We can conclude that the prerequisite for turbophoresis in a turbulent flow is that the turbulence is not homogeneous, but has spatial gradients in the velocity fluctuations. Moreover, turbophoresis is negligible for very small particles, even if a turbulence intensity gradient exists. It is worth mentioning that the turbophoretic velocity depends on the particle's root-mean-square (rms) velocity, which might be different from the fluid rms velocity for larger particles (if the particle inertia is large). When the particles are very small, they stay with the flow, effectively following the eddies, and the two rms velocities become essentially the same. Directly studying the velocity fluctuations of the particles is not possible; however, we can assume a relationship between the velocity fluctuations of the particles and the velocity fluctuations of the fluid.

The source of particles can both be external and internal. During a few preliminary particle measurements we performed in churches, we noted that significant particle emission sources were candle burning (submicron particles during burning, supermicron upon extinguish), infiltration from outdoors (virtually any particle size), and visitors to some extent (supermicron particles). The transport of particles from outdoors to indoors by infiltration suggests the need to consider the tightness of the building envelope to limit soiling.

In experiments on soiling performed worldwide, different influential factors (such as surface roughness, temperature, relative humidity, ventilation rate, particle concentrations, and flow regime such as airflow velocity and turbulence) were identified, several mechanisms studied, and different modelling techniques developed (Chen et al., 2006; Guha, 1997, 2008; Ham dani et al., 2008; He et al., 2005; Lai and Chen, 2006; Lai and Nazaroff, 2005; McMurry and Rader, 1985; Pesavau et al., 1999; Pio et al., 1998; Shimada et al., 1989; Thatcher et al., 2002; Xu et al., 1994; Zhao and Wu, 2007). Surface roughness was found to influence the boundary layer flow close to the surface. A rough surface displaces the boundary layer flow outwards and changes the turbulence structure. For this thesis, I focused on the influential factors of surface roughness and flow regime.

Air motions are generated by natural convection because of the temperature difference between walls and the adjacent air, and boundary layer flows line the vertical surfaces. The magnitude of the total flow in this wall boundary layer flow may be greater than the ventilation flow rate. According to results reported in Mattsson et al. (2011) from measurements in a medieval stone church, the boundary layer flow was approximately 25 times larger than the ventilation flow rate. To prevent discomfort due to downdraught of cold air, radiators or convectors are often located at the perimeters of interior space of a church. Warm plumes from the radiators propagate upwards along the walls, but may collide with the down draught of cold air, giving rise to complicated air flow patterns (Kriegel, 1973). According to previous studies (Mattsson et al., 2011), the variations in the near-wall vertical velocity components were very large, and for short time periods, flow reversals occurred. This finding highlights the complexity of the flow this research examined. Therefore, performing PIV experimentations to quantify this complex flow's characteristics seemed to be logical, despite the practical difficulties of conducting PIV measurements near wall surfaces.

In the series of studies in this category (study of air flow over a wall-mounted radiator), I measured and visualized the entire flow field along the wall over a heating radiator using PIV technique in a full-scale room model. The purpose of this study was to acquire the entire 2D velocity field, and to understand the flow characteristics in the vicinity of wall surface and above the heating radiator. Using in-house software, I obtained the turbulence intensity above the heating radiator and the location where the laminar flow transitioned to turbulent downstream of a heating radiator. Other flow characteristics were also specified, using the measured data, and the velocity field downstream of the heating radiator was investigated. Moreover, I measured and studied the surface structure and geometrical properties of three reference surface samples (wood float finish, brushed finish, and steel float finish) using stripe projection technique. Our team designed a purpose made rig to generate controlled flow over the reference sample surfaces to conduct velocity measurements along the surface. The purpose of this study was to estimate the magnitude of the roughness of different surface samples and to discover any differences in deposition velocity between them. Study results revealed negligible differences among the various surface finishes' influences on the deposition velocity.

4. Measurement Techniques, Experimental Facilities, and Methods

This chapter provides a brief description of the measurement techniques and experimental setups used in the framework of this work. In flow studies, velocity distribution, type of flow, scope of needed information, and physical surroundings often determine the proper measurement technique. Depending on the flow type and measurement required, each method has advantages and disadvantages.

Depending on the flow cases, the primary flow measurement technique for this study was Particle Image Velocimetry (PIV), which has been used for some decades. I established two different PIV setups: one to be performed in a liquid medium (water) and the other in a gas medium (air). In addition to PIV, I used a stripe projection (structured light 3D scanning) system to study the geometrical properties of the surfaces. The various experimental setups used during this work also will be presented.

4.1. Particle Image Velocimetry (PIV)

In today's research in fluid mechanics, popular interest is being directed increasingly to problems in which complex flows predominate. For investigations of such flow fields (such as transition from laminar to turbulent flow, vortical structures, entraining flow fields, airfoils, near-wall flow, and so on), new experimental methods such as PIV are required to capture instantaneously the velocity information across entire flow fields. PIV provides for the first time in measurement history a reliable basis for whole field experimental data in fluids. PIV technique can be for direct comparison with numerical calculations such as CFD, and therefore, for validation of computer codes. During the last years, an increasing number of researchers and scientists have used PIV to investigate the original structure of velocity fields in different areas of fluid mechanics. There are various approaches for recording and evaluating PIV images documented in literature. The PIV technique is growing rapidly, yielding several recent developments, including stereoscopic PIV, 3D-PIV (tomographic and holographic PlV), time-resolved PIV, micro PlV, and combinations of PlV with other optical field measurement techniques. This thesis presents a brief technical description of the basic concepts of PIV technique (how a 2D-PIV works).

4.1.1. Development of PIV

In response to interest in the observation of natural phenomena, experimental tools and measurement techniques have been developed throughout history. These tools first enabled human beings to perform qualitative studies, but as time passed and science and technology developed, new measurement tools emerged that were capable of providing simple quantitative results. Then, in the mid-20th century, more complex measurement tools were developed that could register or compare several different measurements.

Finally in the last century, with the aid of advanced imaging techniques and computing tools, the quantitative measurement of whole flow fields was possible thorough conducting velocimetry of seeded flow in a fluid media, the so-called particle image velocimetry (PIV). Older techniques used to measure flows include laser Doppler velocimetry, hot-wire anemometry, and ultrasonic anemometry. The main difference between PIV and those techniques is that PIV is able to generate instantaneous two-dimensional and even three-dimensional vector fields, while the others measure velocity at a point at a time. Many believe that the development of PIV was a milestone in measurement technique that allowed velocity information of whole flow fields to be registered in very small fractions of a second, considered an instant. The development of PIV began in the 1980s, and then with the expansion of computing capacities and the advent of digital imaging techniques, PIV experienced explosive growth in scope, accuracy, capabilities, and features. PIV has been in great demand for laboratories, experimental applications, and industrial development research.

4.1.2. Principle of Particle Image Velocimetry (PIV)

A PIV system typically consists of several subsystems. Tracer particles (seeding) may be added to the flow, either locally or globally, according to circumstances. A light sheet, placed where the flow is to be measured, illuminates the seeded flow. The illumination occurs at least twice in a short time interval in order to capture the flow pattern at the instant. The light scattered by the seeding particles are recorded on a single frame (older PIV equipment) or on a sequence of frames. Through mathematical evaluation of the PIV recordings, the displacement of the particle images between consecutive illuminations can be determined. Sophisticated post-processing is required to handle the massive amount of PIV data. As the definition suggests, PIV is an indirect measuring technique that determines the tracer particles' velocity instead of the fluid velocity itself. Figure 1 depicts a simple PIV setup for registering the vector fields of a jet flow.

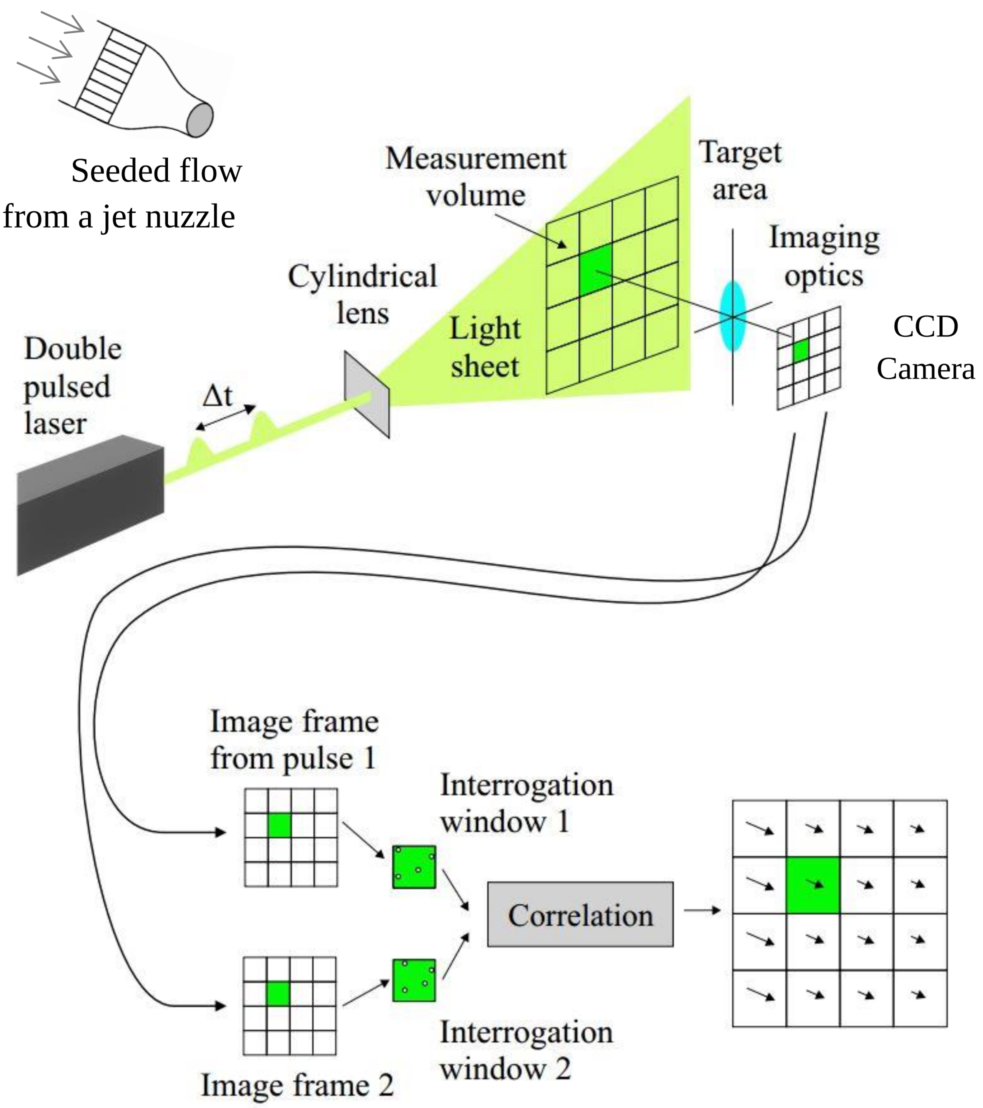


Figure 1. A typical PIV setup (Schiwietz and Westermann, 2004)

In the PIV setup in Figure 1, a digital CCD (charged coupled device) or CMOS (complementary metal-oxide semiconductor) camera captures the laser-illuminated flow field twice and transfers the image data to a post-processing computer. For evaluation of the PIV image pairs, each image is divided into small subareas called interrogation areas. Statistical methods (most commonly cross-correlation) are used to extract the local displacement vectors of the tracer particles from the first and second illumination of the each interrogation area. The tracer particles in a certain interrogation area are assumed to have homogeneous displacement. The local velocity vector is derived by dividing the displacement vector by the time interval between the two illuminations. Setting the single velocity vectors from individual interrogation areas yields the velocity vector field of the whole imaging area. Detailed information about the principle and mathematical background of PIV imaging technique, in addition to experimentation, developments, applications and trends, can be found in the literature (Adrian, 2005; Buchhave, 1992; Elsinga et al., 2006; Melling, 1997; Mizeraczyk et al., 2007; Prasad, 2000a, 2000b; Raffel et al., 2007; Riethmuller et al., 2012; Sandberg, 2007; Schiwietz and Westermann, 2004; Stanislas et al., 2000; Westerweel, 1997; Westerweel et al., 2013).

A sample instantaneous velocity vector field measured using PIV technique is shown in figure 2. The image shows the entire velocity field over a heated radiator for the case of $\Delta T = 15°C$ (see papers 5 and 6). The vector field was obtained from cross-correlation of a double-frame, 2D-PIV image map that comprised 1344×1024 pixels, with interrogation areas of 64×64 pixels, and 50 percent overlap both horizontally and vertically. Thus, the vector field comprises 41×31=1271 interrogation regions and 1271 velocity vectors. A double-frame zoom section of PIV image map taken from Figure 2 is shown in Figure 3. The zoom section comprises 96×96 pixels, including four full interrogation regions of 64×64 pixels, with 50 percent overlap in both directions. The time delay between the two frames was 1250 µs.

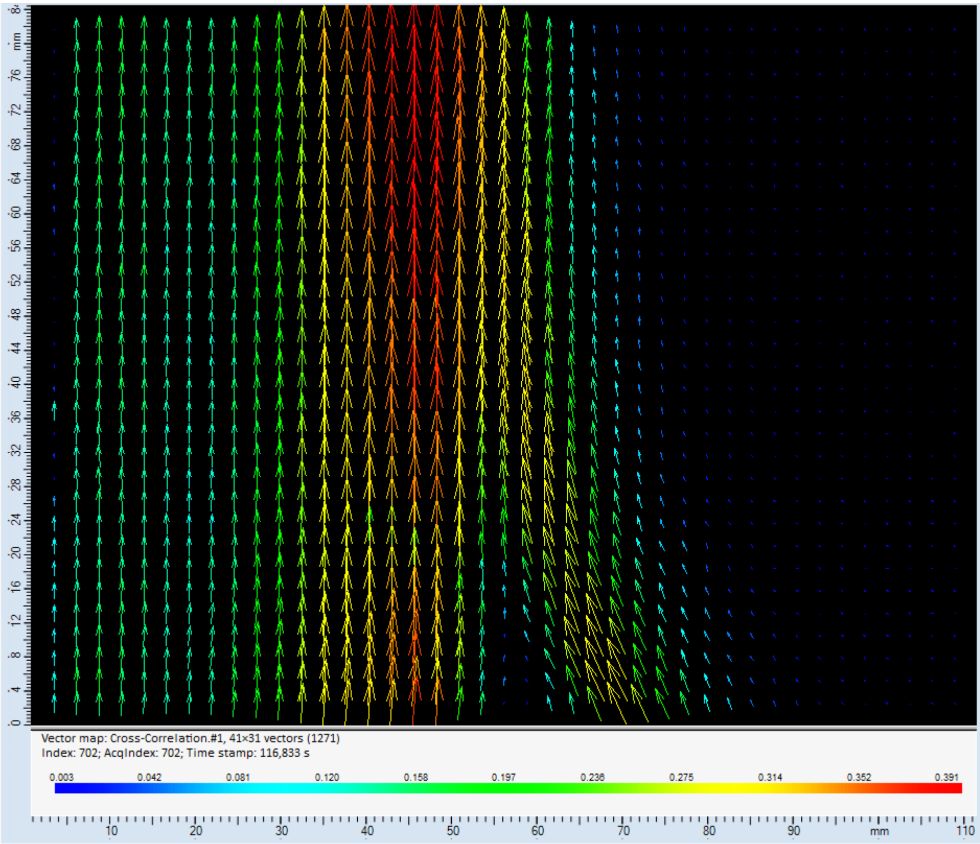


Figure 2. A sample instantaneous velocity vector field obtained from PIV measurement technique (coordinate units in mm)

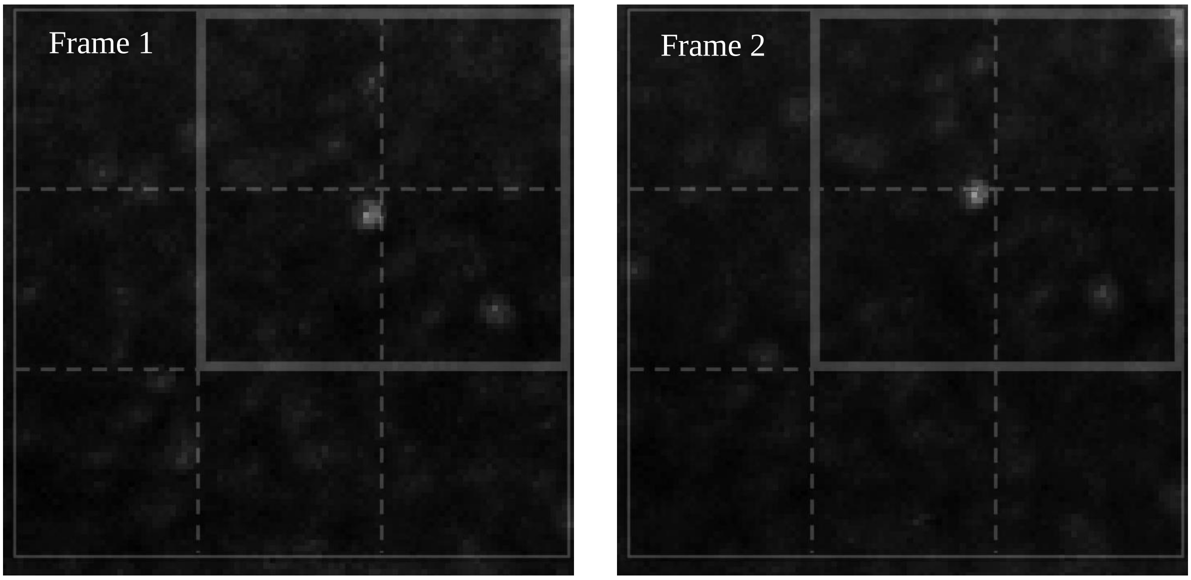


Figure 3. A zoom section of PIV image map taken from Figure 2 and comprising two consecutive frames ($\Delta t = 1250\mu s$). A 64×64 pixel interrogation area is highlighted on the top-right corner of the images.

With modern CCD cameras, a resolution of more than 10 MP is possible, and more than five PIV recordings per second (for full resolution) can be captured. The lower the resolution the more burst (recording) frequency is possible. High-speed imaging with CMOS cameras supports higher resolutions (more than 28 MP) and allows for acquisition in the kHz range for lower resolutions (Dantec Dynamics A/S, 2013a). The evaluation of one PIV recording with thousands of instantaneous velocity vectors is in fractions of a second with today's computers. Moreover, real-time monitoring of the velocity field during PIV measurement is possible, often by reduced precision or reduced frame rate.

4.1.3. PIV Setup Equipment

The following equipment/apparatus is needed to capture the whole vector field of a fluid flow using a typical PIV system setup.

4.1.3.1. Seeding Equipment (Tracer Particles)

Seeding a flow means to introduce minute separate particles (particulates) or other foreign substances into a transparent fluid stream. These particles are generally small enough to follow the flow, but large enough to be identified using a visualization technique. Seeding is the most critical component of a PIV system for obtaining credible vector data. The seeding particles must match the fluid properties (especially fluid density) reasonably well. Otherwise, they will not follow the flow motion well enough to yield satisfactorily accurate results. Therefore, the particles' physical properties must be examined to avoid inconsistency between fluid and tracer particle motion. An important source of discrepancy in PIV measurements is the influence of gravitational force on particles and fluid if the densities of the fluid ρ and the tracer particles ρ_P are not equal. Ideally, the tracer particles should be spherical and have equal density to the fluid media. Moreover, the tracer particles must be both small enough to display a decent latency to the motion of the fluid and large enough to scatter the required amount of light for the camera to capture the particle images.

4.1.3.1.1. Generation of Seeding (Tracer Particles)

The literature contains little information on how to practically generate and distribute tracer particles into the flow under PIV investigation, which makes the process somewhat iterative and experienced-based. Sometimes, seeding can be done easily, and may not even be needed if natural seeding is available (when enough particles suitable for PIV experimentation naturally exist in the flow). But in most experimental PIV studies, including this one, tracer particles (seeding) must be generated and homogeneously distributed in the flow with attention to achieve a decent image contrast and to control particle size and concentration.

4.1.3.1.2. Seeding in Gas versus Liquid Flows

In this work, PIV experimentations were performed in both gas (air) and liquid (water) media. PIV in a liquid flow is mostly conducted in closed-circuit loops such as in a tank, a water tunnel, or in this case, a small-scale room model. Therefore, a high concentration of seeding material can be blended homogeneously in the flow before performing the experimentations. According to Melling (1997), dilutions up to a ratio 1:50,000 are feasible. It is crucial to allow time for the particles to mix thoroughly and uniformly in the operating flow.

Basically, two categories of seeding particles can be used: gaseous bubbles or solid particles. In this research, polyamide seeding particles were good choices for the experiments using a room model filled with water, but these particles are rather expensive for huge volumes. Table 1 provides a list of recommended seeding material for liquid flows (Raffel et al., 2007).

Table 1. Recommended seeding material for liquid operating flows (Raffel et al., 2007; Dantec Dynamics A/S, 2013b*).*

Type	**Material**	**Mean diameter in μm**
Solid	Polystyrene	10–100
	polyamide	5-50
	Aluminum	2–7
	Glass spheres	10–100
	Granules for synthetic coatings	10–500
Liquid	Different oils	50–500
Gaseous	Oxygen bubbles	50–1000

Performing PIV in a gas flow generally requires a supply of tracer particles, which can be very critical for the experimentalists' health. Seeding in a gas flow also can damage equipment, and therefore, the seeding material and approach must be carefully considered. To obtain reliable PIV results, the tracer particles must be distributed into the gas flow in sufficient and stable concentration, which is especially difficult in experiments with local seeding. Particles should be distributed uniformly and coagulation and deposition of particles on the surfaces minimized so that the seeding intensity does not decrease.

The two approaches generally used for seeding in gaseous media are local or global seeding. In local seeding, only the PIV investigation region, or a portion of it, is seeded. In this method, the effect of entraining flow or the velocity field over the whole field is not guaranteed. In global seeding, the tracer particles are introduced to the flow well upstream of the measurement region or well in advance in the measurement volume, which distributes the tracer particles homogeneously in the whole region. Global seeding is preferable because uniform seeding is guaranteed everywhere in the experimentation region. With global seeding, velocity vectors over the entire flow field of a PIV experiment and the surrounding effects, such as entrainment and secondary vortices, are represented. Mounting the seeding probe in the proper places will avoid flow disturbances. Table 2 lists recommended seeding material for gas flows (Raffel et al., 2007).

All PIV experimentations presented in this report were carried out using global seeding. For the PIV experimentations on air flow above a wall-mounted radiator, a SAFEX FOG 2001 smoke generator with "normal power mix" (for disco smoke) as the seeding raw material was used. The assumption was that this method would generate almost uniform tracer particle distribution with particle diameter of approximately 10 micrometers.

Table 2. Recommended seeding material for gas operating flows (Raffel et al. 2007).

Type	Material	Mean diameter in μm
Solid	Polystyrene	0.5–10
	Alumina Al_2O_3	0.2–5
	Titania TiO_2	0.1–5
	Glass micro-balloons	30–100
	Glass micro-spheres	0.2–3
	Granules for synthetic coatings	10–50
	Dioctylphathalate	1–10
	Smoke	<1
Liquid	Different oils	0.5–10
	Di-ethyl-hexyl-sebacate (DEHS)	0.5–1.5
	Helium-filled soap bubbles	1000–3000

4.1.3.2. Illumination Sources

Currently, PIV experimentations utilize high-frequency LED lasers and strong flash lamp lasers as light sources for measurements. A laser (light amplification by stimulated emission of radiation) is a device that illuminates through a process of optical amplification based on the stimulated emission of electromagnetic radiation. Lasers are characterized by their coherence, typically expressed through an output of a narrow beam with very limited diffraction. Lasers are able to emit monochromatic light with high energy intensity, which can easily be formed into light sheets suitable for illuminating and recording tracer particles with insignificant chromatic aberration. Two illuminations are needed in a very short time span to provide the minimum of two particle images required to perform the correlation. Therefore, dual cavity lasers capable of emitting two laser peaks in very small fractions of a second have been specially designed for PIV measurements.

A typical laser consists of a gain medium (laser material), a mechanism to supply energy (pump source), and a mirror arrangement to provide optical feedback. The gain medium or laser material has special properties enabling it to amplify light by stimulated emission (Siegman, 1986). The principle set-up of a laser emitter device is shown in Figure 4 (Eichler et al., 2005). Light from an LED or flash lamp is amplified by induced emission within an active medium (an atomic or molecular gas, semiconductor, or solid material). The active medium or laser material has an intensity- and frequency-dependent gain factor. The beam goes forward and backward between the two mirrors of a resonator. The threshold of laser oscillation requires a gain factor exceeding the total losses occurring in the round-trip. The resonance condition determines the frequency of the beam.

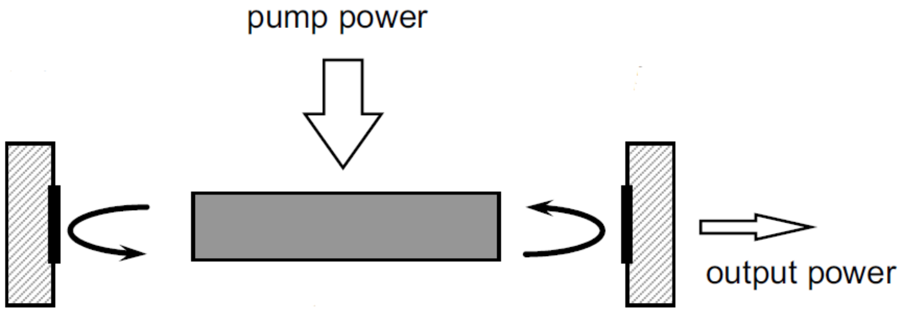


Figure 4. Schematic set-up of a laser oscillator (Eichler et al., 2005).

Various types of lasers are used in science and technology based on their light sources and gain media, such as helium-neon lasers (He-Ne lasers A = 633 nm), copper-vapor lasers (Cu lasers A = 510 nm, 578 nm), argon-ion lasers (Ar+ lasers A = 514 nm, 488 nm), semiconductor lasers (very compact), ruby lasers (CrH lasers A = 694 nm), and neodym-YAG lasers (Nd:YAG lasers A = 532 nm). The neodym-YAG (Nd:YAG) laser is the most important solid-state laser commonly used for PIV measurements. In Nd:YAG lasers, the beam is generated by Nd3+ ions. All PIV investigations for this thesis utilized Nd:YAG lasers with a wavelength of 532 nm.

4.1.3.3. Light Sheet Optics

After the laser is generated, the laser beam becomes a light sheet that is needed to perform PIV measurements. This transformation requires passing the laser beam thorough a set of lenses, or so-called light sheet optics. Light sheet optics, which may be set up in various ways based on laser beam properties and usage, consist of a combination of cylindrical and spherical lenses. The cylindrical lens, which is essential for generating the light sheet, expands the beam into a plane; the spherical lenses generate a light sheet of specific height and compress the plane into a thin light sheet suitable for capturing particle images. An optical combination can be created to adjust the light sheet thickness. A typical three-element light sheet optic, consisting of a cylindrical lens and two spherical lenses, is shown in Figure 5. In this optical setup, the light sheet height can be adjusted by changing the cylindrical lens properties. Thickness is easily adjusted by shifting the spherical lenses with respect to each other.

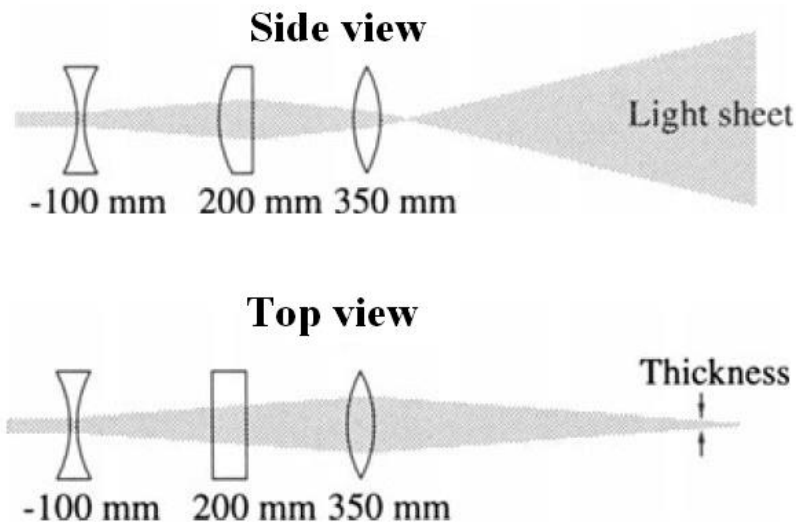


Figure 5. A typical three-element light sheet optic, consisting of a cylindrical lens and two spherical lenses (Raffel et al. 2007).

4.1.3.4. Image Recording

To conduct PIV analysis on the flow, two exposures of the particle images from the flow are required. The proper objective must be connected to the PIV camera to focus on and visualize the particles in the investigation area. Originally, chemical cameras for PIV imaging could not capture dual (or multiple) frames at high speeds. Therefore, both exposures were captured on the same frame the moment the laser guns fired, which created particles images of the first and second shot on the same picture. To obtain displacement vectors on the same frame, a process called autocorrelation is performed; however, the direction of the flow is unclear as a result of autocorrelation. The first generation of digital PIV cameras had the same technical inability when autocorrelation was used to determine displacement, and thus, velocity vectors. After a while, faster digital cameras with CCD or CMOS sensors were developed that could capture two frames at high speeds, synchronous to the laser fire, which were suitable for PIV experimentations. The PIV image pairs are directly transferred from the digital PIV camera to a computer. Each light exposure can be captured on one separated frame, making it possible to perform cross-correlation analysis on the computer to find a more accurate displacement vector with known direction.

Typical camera sensors have the following limitations:

- The high multiple frame exposure speed has limited pairs of shots
- If good vector results are demanded, the resolution is limited so that the whole field of interest in the flow does not fit in one single measurement
- Limited dynamic range
- Limited quantum efficiency or QE (the percentage of photons hitting a photo-reactive device that produces charge carriers, measured in electrons per photon)
- Existence of noise

Outstanding progress has been made in the development of PIV cameras in recent years. The image quality has become unprecedentedly high in terms of resolution, QE, dynamic range, and noise levels. The frame rates of newer cameras have even reached the KHz level (for lower resolutions). The PIV cameras used in this research were older ones, but they could do a decent job in the light intensities, frame rates, and other conditions as defined.

4.1.3.5. Synchronizer

The camera(s) and the laser cavities must be synchronous to capture PIV images with a specified time difference between the frames and within the bursts. The camera(s) capture an image when the laser sheet illuminates the velocimetry target, which occurs sequentially with the operator setting the time differences according to flow velocity. The synchronizer acts as an external triggering agent for both the camera(s) and the laser. Most synchronizer systems are digitally controlled by a computer. The synchronizer must be very accurate to be able to set the timing of each frame of the camera's sequence in connection with the firing of the laser in very tiny time lapses (nanoseconds). Being able to specify and control this timing is critical to determine the velocity of the fluid in the PIV analysis. With the advent of novel PIV systems such as stereoscopic or tomographic PIV and time-resolved PIV techniques, synchronizers offer the means to control several flash lamps, Q-switches, and multiple camera exposures.

4.2. Surface Measurement Using Structured-Light 3D Scanners

Surface measurement or surface metrology refers to measuring the topography of a surface. Surface measurement is an umbrella term that encompasses such things as surface shape, finish, profile roughness, texture, and structural characterization (Zygo Corporation, 2015). There are several methods for surface measurement with different levels of accuracy and application. Atomic force microscopy (AFM) or scanning force microscopy (SFM) is a very high-resolution type of surface scanning. AFM has a resolution of fractions of a nanometer, or more than 1000 times better than the optical diffraction limit. For this research, a structured-light three-dimensional (3D) scanner system was required based on the application and the resolution needed in the experiments. A structured-light, three-dimensional (3D) scanner system is a device for measuring with a resolution of micrometers the 3D shape of an object using projected structured light patterns (such as stripes) and a camera system.

4.2.1. Principle of Structured-Light 3D Scanner System

This system uses a technique based on projecting an array of structured light patterns on a surface and observing the distortions from another perspective. Projecting a narrow band of structured light (for example, in the shape of stripes or sinus waves) on a random surface generates a line of illumination that does not appear the same from different perspectives than the projector. This distortion can be recorded and used in order to obtain an exact geometric reconstruction of the surface shape. Although several types of structured-light projection are possible, patterns of parallel stripes are most widely used (stripe projection). This method provides enough information to acquire multitude samples simultaneously. Seen from different positions, the pattern appears geometrically distorted in relation to the object's surface shape. The surface geometry is reconstructed by post-processing the distortion of the stripes on the surface, scanned from several positions. Figure 6 shows the geometrical deformation of projected striped patterns onto a surface. The displacement of the stripes viewed through different cameras allows retrieval of the detailed 3D coordinates of the surface's geometry.

4.3. Small-Scale Ventilated Room Model

The experiments described in papers 1, 2, and 3 were performed in a small-scale room model. This 2D model was 30×20×1.0 cm^3 in dimension and used water with polyamide seeding particles (PSP) that were 20 μm in diameter as the operating fluid, with a closed loop circulation. The inflow and outflow to the model took place through a circular cross-sectional area of a diameter of D=9 mm. Since the supply slot was almost equal to the width of the model, a 2D jet stream was generated in the room model (the ideal 2D model of infinite width and with a slot width equal to the room width cannot be realized in practice). The size of the model made it possible to investigate the 2D velocity vector field on certain stagnant regions.

To measure velocity, the PIV system consisted of a Spectra Physics 400 mJ double pulsed Nd:Yag laser operating at 15 Hz as illumination source and a double-frame CCD camera Kodak ES1.0 8-bit with 1018×1008 pixels. A mechanical pulse generator was installed before the inlet to the model, which enabled flow pulsations with adjustable frequency to be created. A rotary flowmeter was placed in the return circuit before the water reserve tank (Figure 7) to monitor the flow rate on a computer display with a home-designed LabView program. Figure 8 shows the experimental setup in the small-scale room model including a) schematic of the experimental PIV setup, and b) a photo of the experimental model setup plus reflector mirror, light sheet optics, and camera (laser is not shown).

4.4. Surface Profile Measurement

Recorded surface height profiles for three sample plaster finishes (paper 4) were obtained from structured-light 3D scanning, using striped patterns as the structured light. In that setup a "GFM Primos Compact" system from GFMesstechnik was used for scanning the sample surfaces. The measurement area covered by the system was 30 × 40 mm^2 with an x and y resolution of 60 μm and z (height) resolution of 4 μm. The measurement results were analyzed and processed with the computer software, GFM PRIMOS ver. 5.6. Figure 9 shows examples of ordinary 2D photo and 3D scanned surface model of surfaces, including a) wood float finishing, b) brushed finishing, and c) steel float finishing.

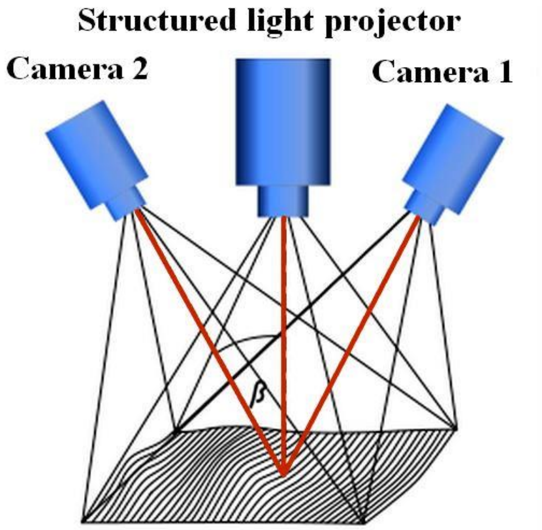


Figure 6. Structured-light 3D scanner system (pattern projector and recording system comprising two cameras)

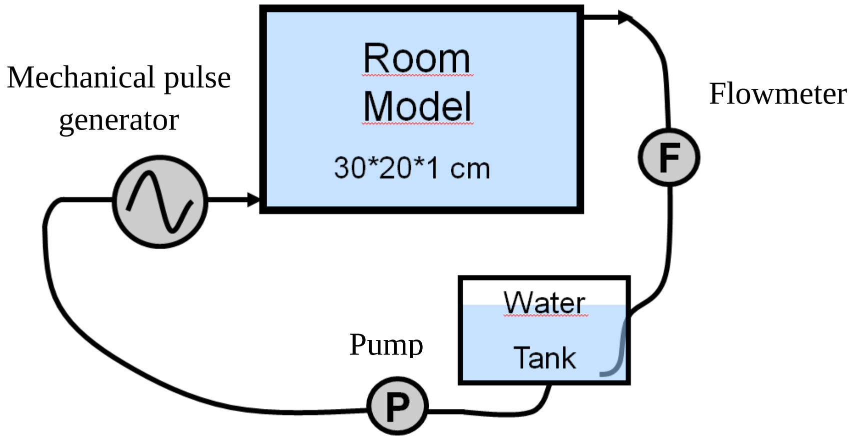
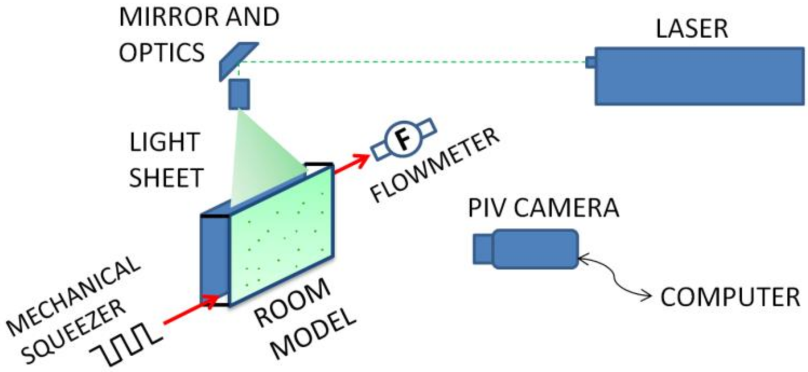


Figure 7. Water circulation loop

a)



b)

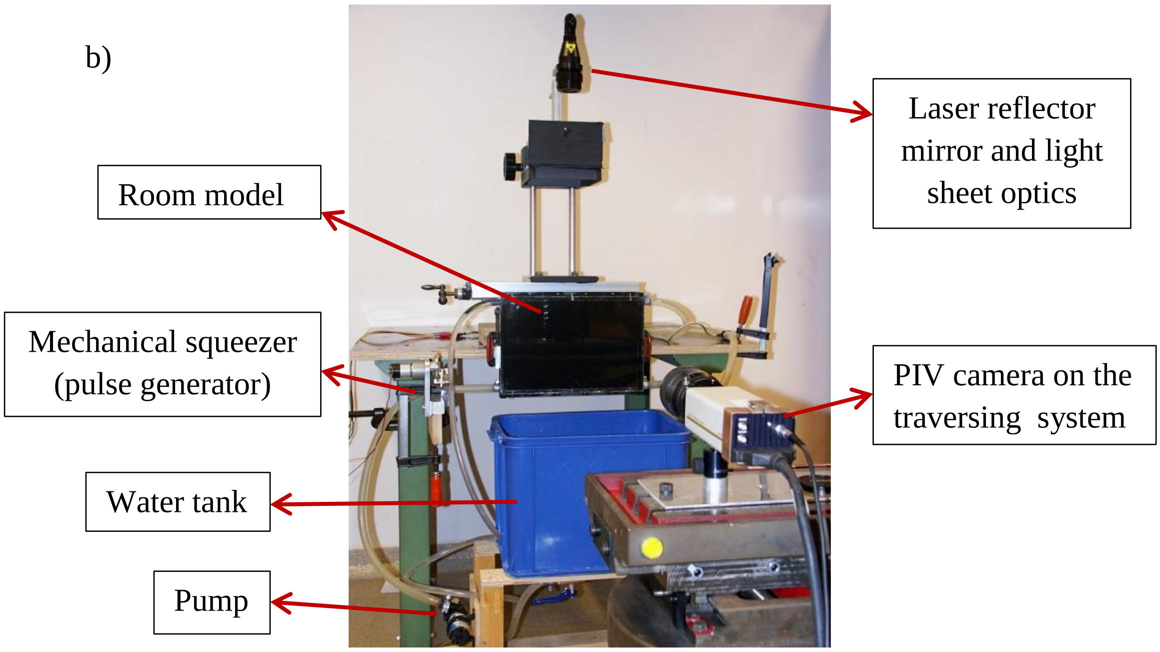
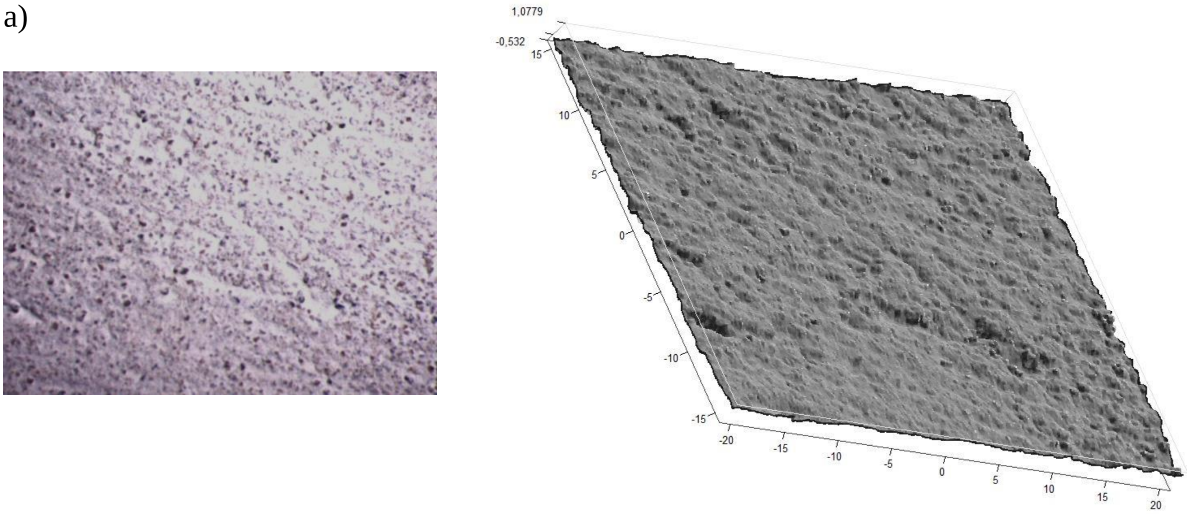
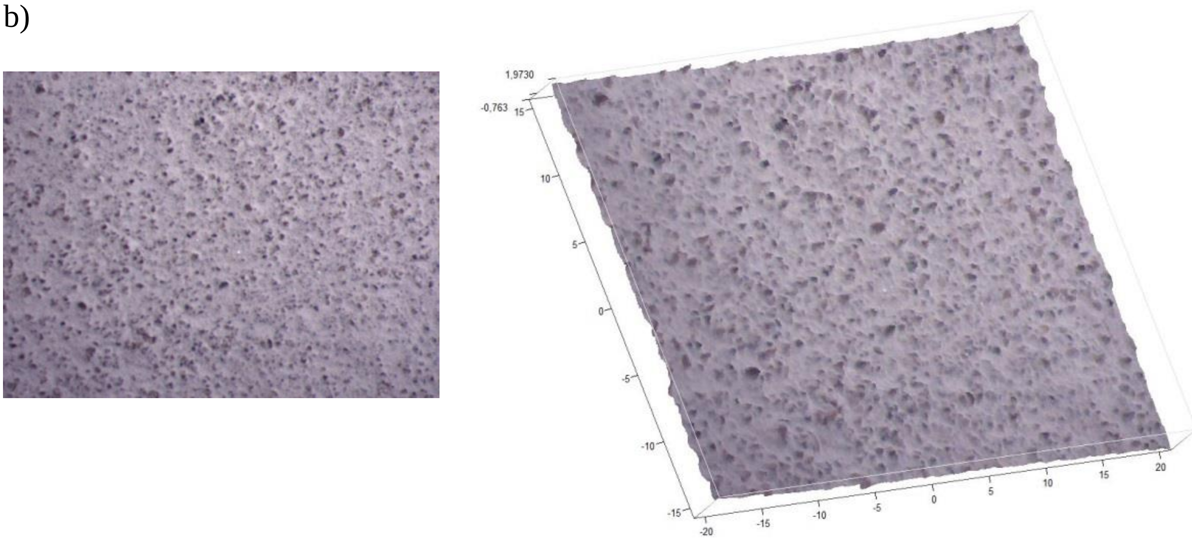


Figure 8. a) Schematic of the experimental PIV setup, and b) photo of the experimental model setup

a)



b)



c)

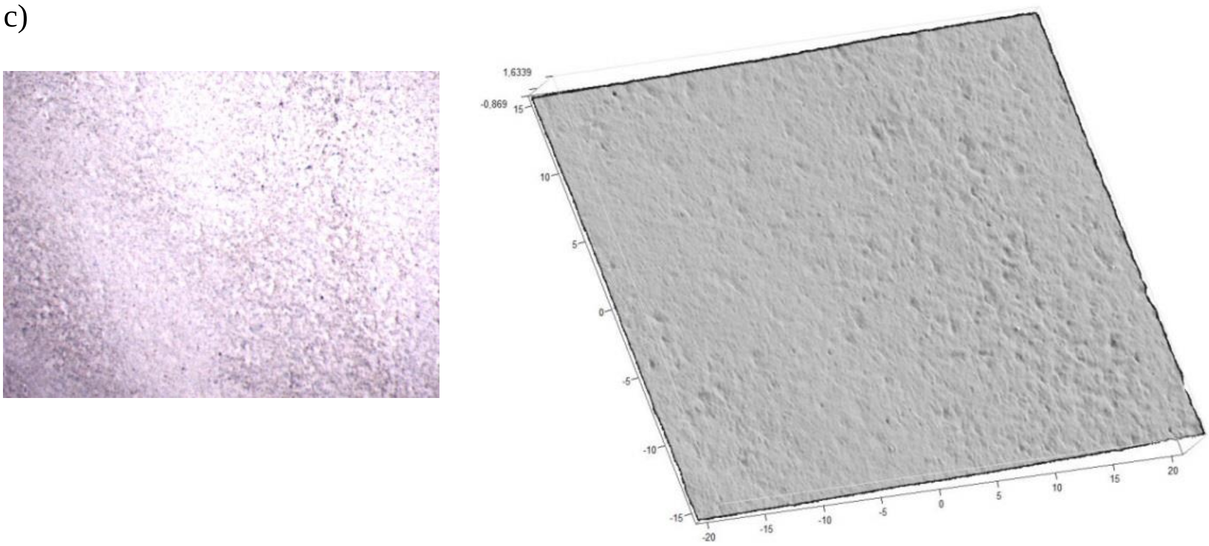


Figure 9. 2D photo (left) and 3D scanned surface model (right) of surfaces with a) wood float finishing, b) brushed finishing, and c) steel float finishing

4.5. Air Flow Measurement over a Wall-Mounted Radiator

To obtain high-quality PIV measurements, an enclosure with dimensions of 3(w) × 2.4 (h) × 2.5(d) m was designed and built around the radiator (see Figure 10). An electric radiator with dimensions 108(w) × 60(h) × 4(d) cm was mounted on the outdoor wall. The measurements and visualizations (both PIV and ordinary video visualizations) were conducted over the radiator adjacent to the wall surface. With the enclosure, a well-distributed global seeding could be achieved, a prerequisite for a high-quality PIV measurement. The reflection of the laser on the wall surfaces reduced the quality of the PIV measurement and generated a lot of rejected vectors. To minimize this reflection, the wall was covered with a non-reflexive black texture, which was tightly stretched near the measurement plane to prevent the effects of macro roughness from the wall surface on the air flow. Conventional smoke visualizations indicated that the flow was unaffected by the black texture.

To measure the velocity field, I used a PIV system consisting of a 15-Hz New Wave Solo PIV 50-mJ double-pulsed Nd:YAG laser operating at 6 Hz for illumination, as well as a double-frame, high-sensitivity 12-bit CCD camera HiSense MKII with a resolution of 1344 × 1024 pixels. An AF Micro Nikkor objective with a focal length of 60 mm was mounted on the CCD camera. Adequate seeding is required to conduct high-quality PIV investigations, and therefore, to capture both plumes and the entrainment from the room environment, a global, homogeneous seeding with appropriate seeding intensity must be provided. For this general seeding purpose, I used a SAFEX FOG 2001 smoke generator with "Normal power mix" as fog generating liquid, which gave satisfactory measurement results. The liquid comprised a minimum 70 percent fog active substance content. The produced fog had medium durability, and depending on temperature and ventilation conditions, remained for 10 to 30 minutes (Safex-chemie gmbh, 2015). Figure 10 shows a photograph of the experimental setup, comprised of the wall-mounted radiator and the PIV system.

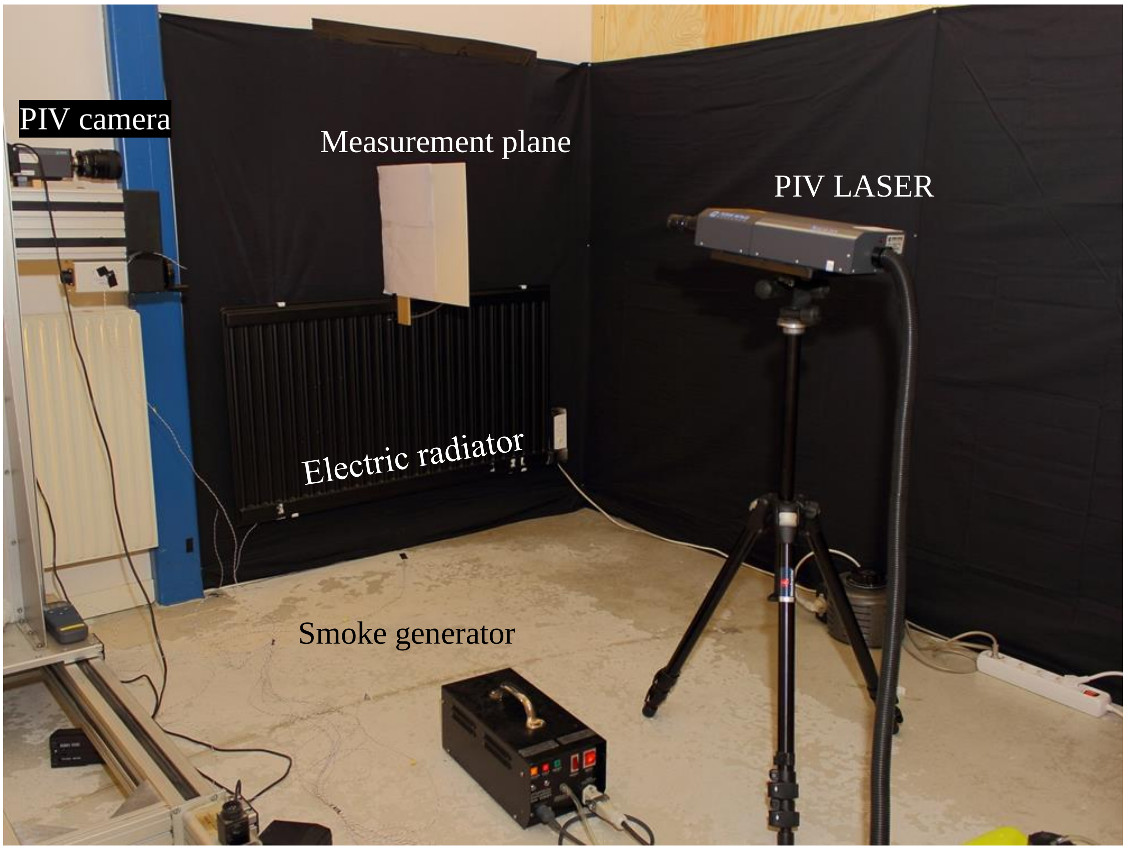


Figure 10. Experimental setup comprised of the electric radiator, smoke generator (for seeding the room globally), double-pulsed laser, and CCD camera on the traversing system.

4.6. In-House Software

The main focus in all PIV measurement experiments performed in this research was to acquire high-quality, whole-field velocity vectors in a time series. To obtain a high quality vector field with a low rate of rejected vectors (roughly less than 5 percent rejected vectors in the investigation region), PIV measurements were performed in smaller domains. Each measurement domain overlapped with neighboring domains in order to cover the whole field. The physical parameters such as temperature were kept constant, since the measurements were conducted in different domains and at different instants of time.

The PIV image pairs from measurement experiments, consisting of several measurement domains, were processed with PIV software packages (Dantec Flow Manager and Dantec Dynamic Studio) to obtain the whole-field velocity vectors. The velocity vectors were obtained from determining cross-correlation (or in some cases, average-correlation) for 32×32 or 64×64 pixel interrogation areas with 50 percent overlap in both horizontal (x) and vertical (y) directions. The resulting vector fields from different experiments comprised several domains and overlapped with each another. Therefore, they were cropped in such a way that a complete vector field could be created from tiling the domains beside each other.

All the statistical data resulted from post-processing the exported velocity vector data with in-house developed programs in MATLAB. These velocity vector data came from cross-correlation of all PIV image pairs across the overlapped domains, with 32×32 or 64×64 pixel sized interrogation areas and 50 percent overlap in x and y directions. Certain statistical data were calculated with the in-house software based on the type of experiment, results, and analogy applicable for various research papers. The calculated statistical data included standard deviation, covariance, average velocity vectors, relative turbulence intensity values, and turbulent kinetic energy (TKE) values.

In this thesis, the x-component of the velocity vector is referred to as “u,” and the y-component of the velocity vector as “v.” Using the in-house developed programs, the statistical mean and the root mean square (rms) deviation of the fluctuations of velocity components (u and v) were manipulated from the instantaneous vector fields for each interrogation area, using the following equations:

$$\bar{u} = u_{average} = \frac{1}{n}\sum_{i=1}^{n} u_i \quad (1)$$

$$\bar{v} = v_{average} = \frac{1}{n}\sum_{i=1}^{n} v_i \quad (2)$$

$$\sigma_u = u_{rms} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(u_i - \bar{u})^2} \quad (3)$$

$$\sigma_v = v_{rms} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(v_i - \bar{v})^2}. \quad (4)$$

The covariance of the velocity components u and v (or Reynolds stresses RS_{xy}) is defined as (where E[x] is the mean value of parameter x)

$$\overline{\acute{u}\acute{v}} = \sigma(u, v) = E\ [(u - E[u])(v - E[v])], \quad (5)$$

and was compiled from

$$RS_{x,y} = \overline{\acute{u}\acute{v}} = \frac{1}{n}\sum_{i=1}^{n}(u_i - \bar{u})(v_i - \bar{v}). \quad (6)$$

Assuming the out-of-plane velocity component is zero, the relative turbulence intensity value (T_i) at each point, based on the x-component of the velocity vectors (u) and turbulent kinetic energy (TKE) values at each point, were compiled from:

$$T_{i,x} = {}^{\sigma_u}/_{\bar{u}} \quad (7)$$

$$TKE = \frac{1}{2}({\sigma_u}^2 + {\sigma_v}^2.) \quad (8)$$

5. Summary of Results, Discussion and Conclusions

The general approach in mechanical ventilation is to use a constant flow rate, forced convection system as inflow. This method can cause several problems, such as draught, stagnation at certain occupied locations, and subsequently low ventilation efficiencies. Moreover, it consumes a big share of building energy. An alternative to increase ventilation quality while lowering energy consumption (an interest in this work) is to introduce rapidly varying inflows (within the range of 0.3 Hz to 0.5 Hz). This solution was considered to have potential for reducing stagnation and increasing ventilation efficiency. In the investigations, I considered two different flow rates Q_1=0.16 and Q_2=0.24 lit/min, located on either side of the threshold flow rate (Q_{tr}), which corresponded to the onset of natural role-up of vortices in the outer shear layer of the wall jet. The inflow variations were applied to Q_1 and Q_2 to compare the effects of varying inflow versus increasing inflow rate. The experiments were performed using a 2D small-scale room model with the dimension 30×20×1.0 cm^3 with water as operating fluid. A PIV system was used to measure the velocity field.

The results indicated that the calm region with large stagnation zones, without pulsating inflow conditions, became more active when inflow variations were introduced; that is, the stagnation points moved off the occupied zone in favorable directions. In addition, the pulsation increased the vorticity, and in turn, the mixing.

Using an in-house vortex detection program, we were able to show that with an increase in pulsation frequency, or alternatively in the flow rate, the stagnation zones were reduced in size, and the distribution of vortices became more homogeneous over the considered domain. The number of vortices in all scales increased by a factor of four, and the swirl strength increased by about 50 percent simply by applying the inflow pulsation. Two major vortex length scales were identified in the flow, namely 0.6 and 0.8 inlet diameters, and the spectrum of vortex diameters become broader when pulsation was applied. The logical conclusion is that the positive effect of enhanced mixing through increasing the flow rate could equally be accomplished through a pulsating inflow.

In another study on the same room model, the flow rate was constant and only one pulsation frequency (0.5 Hz) was applied. The purpose of the study was to explore the effect of flow variations on the stagnant zones of the occupied region (far-field) and the zone just downstream of the supply jet. The entire vector field of these regions was measured using the PIV technique, and the average vector fields and streamlines before and after application of flow variations were compared. Moreover, the levels of turbulent kinetic energy, the standard deviation, average velocity component values, and relative turbulence intensity along a horizontal line in the occupied region were analyzed and compared.

By applying a pulsation while keeping the flow rate constant, the streamline plots in the far-field occupied region indicated an improved flow map, considering stagnation points. This implies that the occupied region with large stagnation zones for the constant inflow became more active because the stagnation points moved away in a favorable direction from a mixing point of view. In addition, the mean turbulent kinetic energy levels increased, which means that in the far-field occupied region, stronger eddies developed, which can be expected to improve mixing. With a pulsating inflow, the streamlines of the near-field indicated an improved mixing.

This fundamental study was conducted using a small-scale, water-filled, 2D model, in contrast to a full-scale ventilated room with a pulsatile air circulation system. The results describe in this thesis and the attached papers reflect only the potential to devise a more effective air circulation system; how the application of pulsations to the inflow would affect ventilation quality and energy consumption in reality has not yet been examined. Also, the comfort and cognition studies must be examined in reality as future work. Without the constraints of time and money, the measurements of this fundamental study could have been made with a high-resolution, 3D PIV system to acquire a larger investigation area and 3D vector results in a 3D room model.

Another part of this thesis was aimed at finding ways to save energy in historic buildings, while considering preservation of historical and aesthetical values. Studies were conducted in relation to particle deposition on surfaces, including surface structures, and measurement of airflow over a wall-mounted radiator. Radiators are commonly used in Scandinavian countries for heating, and airflow over a heated panel radiator is a decisive factor in room ventilation, particle deposition on wall surfaces, and energy efficiency. The properties of surfaces interfere with nearby air motions and therefore can influence particle deposition. Also, roughness of surfaces increases particle deposition rates.

In a related study, I investigated surface samples finished in wood float finish, steel float finish, and brushed finish. The geometrical properties of the surfaces were experimentally documented using a structured-light 3D scanner. The micro-structures of the three different surfaces had different geometric roughness values. The resistance to airflow along the surface and the turbulence generated by them were measured by recording the boundary layer flow over the surfaces in a special flow rig. The study results showed that the types of surface finishing methods differed very little in their resistance and therefore their influence on the deposition velocity is probably small.

In addition, I measured and visualized the entire flow field along the wall over a wall-mounted heating radiator using the PIV technique in a full-scale room model. The purpose of this study was to acquire the entire 2D velocity field, and to understand the flow characteristics near the wall surface above the radiator. The flow pattern was visualized using an ordinary video camera and flow streamlines from the average correlation of the PIV images. The velocity vector maps from PIV measurements of this experimental study were properly correlated, overlapped, validated, and post-processed using in-house software to provide the average streamlines and other statistical information, such as standard deviation, average velocity, and covariance of the entire vector field. The results showed that for a typical room, the flow over the radiator becomes agitated after an ordinate of $N = 5.00–6.25$ over the radiator's upper level, in which N is the dimensionless length based on the thickness of the radiator. The results of this study's statistical analysis correspond with PIV visualization and ordinary video visualization results.

Future research could examine the relationship between long-term in-situ particle deposition (or surface blackening) and the flow field over a radiator. Also, without time and financial constraints, a study could be done in a climate-controlled room, with a high resolution, 3D PIV system to get 3D vector results under controlled room temperature and boundary conditions.

6. Short Presentations of Each Research Paper

Paper 1

Sattari A, Fallenius BEG, Fransson JHM, Sandberg M (2011, June) PIV visualization study in a two-dimensional room model with rapid time varying ventilation flow rates. Proceedings of ROOMVENT International Conference, Trondheim, Norway.

This article is about a PIV visualization study on an innovative ventilation method that featured rapidly varying inflows in a small-scale, two-dimensional, water-filled room model. The work was an experimental study of the flow using 2D PIV technology.

Mechanical ventilation generally uses a forced convection system with a constant flow rate as the inflow, which can cause draught, stagnation at certain occupied locations, and low ventilation efficiencies. This study looked at an alternative system to increase ventilation quality by introducing rapidly varying flow variations (0.3 Hz to 0.5 Hz) to reduce stagnation and increase efficiency. Two set of base flow rates also were considered to compare the effects of varying inflow versus increasing inflow rates.

The results showed that the calm region (with large stagnation zones, without pulsating inflow conditions) became more active when inflow variations were introduced, which moved the stagnation points in favorable directions off the occupied zone. In addition, the pulsation increased the vorticity, and thereby, the mixing.

Authors' contributions: Sattari conducted the PIV measurements and video visualizations with assistance and guidance from Fallenius and Fransson. Sattari assisted in making the new room model and initiated changes to the model to suit PIV measurements. Sattari and Fallenius analyzed the PIV measurement results jointly. Sattari wrote the article with assistance from Fallenius and minor assistance from Fransson and Sandberg. Fransson and Sandberg supervised the project, and Sandberg initiated the project idea.

Paper 2

Sattari A and Sandberg M (2013) PIV study of ventilation quality in certain occupied regions of a two-dimensional room model with rapidly varying flow rates. *International Journal of Ventilation* 12(2): 187–194. (Parts of this work were published as PIV study of ventilation quality in certain occupied regions of a 2D room model with rapidly varying flow rates. Proceedings of the 10th International Conference on Industrial Ventilation, Paris, France, September 2012

Similar to the study in paper 1, this study used the small-scale ventilated room model experimental setup to examine the application of rapidly varying inflow to a ventilated room. But unlike the study in paper 1, the example in this study had a constant flow rate and only one pulsation frequency (0.5 Hz) was applied. The purpose of the study was to explore the effect of flow variations on the stagnant zones of the occupied region (far-field) and the zone just downstream of the supply jet.

The entire vector field of these regions were visualized using PIV technique and the average vector fields and streamlines were compared before and after application of flow variations. In addition, the study analyzed and compared the levels of the turbulent kinetic energy, the standard deviation, average velocity component values, and relative turbulence intensity for the horizontal direction along a horizontal line in the occupied region.

The vector maps indicated that the calm near-field domain became more active with the pulsated inflow, developing a growing stream of flow circulation in the whole room model. The streamlines for the varying inflow reached higher ordinates to the far-field compared with those of the constant inflow. This phenomenon indicated that pulsations produced a better mixing within the whole model domain. In addition, the mean turbulent kinetic energy levels increased with the application of pulsations. Therefore, in the far-field occupied region, stronger eddies were developed, which we can expect to improve mixing.

Authors' contributions: Sattari conducted all the PIV measurements, assisted in making the new room model and initiated to fix the new room model to suit PIV measurements. Sattari also did the programing, analyzed all the PIV measurement data, and made all the graphs and figures depicting the results. Sattari wrote the article, which Sandberg reviewed and supervised, writing parts of the introduction. Portions of this work were presented at the 10th International Conference on Industrial Ventilation, Paris, France, in 2012.

Paper 3

Fallenius BEG, Sattari A, Fransson JHM, Sandberg M (2013) Experimental study on the effect of pulsating inflow to an enclosure for improved mixing. *International Journal of Heat and Fluid Flow* 44: 108–119.

Also similar to the study in paper 1, this study used the small-scale ventilated room model experimental setup and the application of rapidly varying inflow to a ventilated room; parts of this paper were incorporated into paper 1.

Optimal control of inlet jet flows has broad interest for enhanced mixing in ventilated rooms. This study tested the hypothesis that a pulsating inflow has potential to improve ventilation quality through enhanced mixing that reduces stagnation zones. As in paper 1, the experiments were performed in a small-scale two-dimensional water model using Particle Image Velocimetry.

Using an in-house vortex detection program, we showed that an increase in pulsation frequency, or alternatively, in the flow rate reduced the size of the stagnation zones and resulted in a more homogeneous distribution of vortices over the considered domain. The number of vortices in all scales increased by a factor of four, and the swirl-strength increased by about 50 percent, simply by applying the inflow pulsation. In addition, the vortices became balanced in their rotational directions, as validated by the symmetric Probability Density Functions of vortex circulation. Two major vortex length scales were identified in the flow –

0.6 and 0.8 inlet diameters – and the spectrum of vortex diameters were broader with the pulsation.

The logical conclusion of this study was that the positive effect of enhanced mixing through increasing the flow rate could be accomplished equally through applying a pulsating inflow.

Authors' contributions: Sattari conducted all the PIV measurements and video visualizations with some assistance and guidance from Fallenius and Fransson. Sattari assisted with making the new room model and initiated changes to the model to suit PIV measurements. Sattari and Fallenius analyzed the PIV measurement results jointly, and Fallenius conducted the vortex statistics analysis and results. Sattari and Fallenius wrote the report with some assistance from Fransson and Sandberg. Sandberg initiated the project and the idea, and supervised the project with Fransson.

Paper 4

Sandberg M, Sattari A, Mattsson M (2013, September) Plaster finishes in historical buildings – Measurements of surface structure, roughness parameters and air flow characteristics. Proceedings of the 3rd European Workshop on Cultural Heritage Preservation (EWCHP) Bozen/Bolzano, Italy, 69–75.

As part of the Swedish Energy Agency's research project, "Save and Preserve" (*spara och bevara*), this study focused on soiling and surface structure. Saving energy while preserving old buildings, such as churches, from damage was the main goal for historic building conservation in this project.

The properties of surfaces interfere with nearby air motion, and therefore, can influence particle deposition. Also, roughness of surfaces can increase particle deposition rates. Therefore, surfaces in historic buildings affect blackening caused by particle deposition.

In this study, we investigated surfaces with wood float finish, steel float finish, and brushed finish. As a reference comparison, an MDF board was used. The geometrical properties of the surfaces were documented using the stripe projection method. The resistance to airflow along the surfaces and the turbulence that the surfaces generated were investigated by recording the boundary layer flow over the surfaces in a special flow rig. The study results showed minor differences between surface finishes on the deposition velocity, despite their different geometric surface roughness values.

Authors' contributions: Sattari performed the measurements on the surface structures using a structured-light 3D scanner. Sattari analyzed the acquired data using special software to map the surface profiles and information on the surface roughness. Sandberg wrote the article, except the section about surface metrology. Mattsson performed the velocity measurements in the field trial (whereas research engineer Leif Claesson performed the velocity measurements in the flow rig). Sattari wrote the section of the article regarding surface structures (including the related graphs), and reviewed the article.

Paper 5

Sattari A, Sandberg M (2014, October) Particle Image Velocimetry (PIV) visualization of air flow over a wall-mounted radiator. Proceedings of ROOMVENT International Conference, São Paulo, Brazil, 230–236.

This work examined a common room heating technique using a wall-mounted radiator without forced convection. In this system, cold air in the room adjacent to the radiator's warm surfaces is heated, rises along the wall surface above the radiator, and then is circulated into the room. The properties of these heated plumes are important for assessing the risk of soiling of walls through particle deposition driven by turbophoresis. Therefore identifying the transition from laminar to turbulent flow is important, which was a focal point in this study.

In this experimental study, we visualized the airflow over an electric radiator using the two-dimensional Particle Image Velocimetry (2D PIV) technique. Vector maps were validated by size and peak, and post-processed to provide average streamlines.

In the near wall PIV measurements, some practical problems arose: the generation of a homogeneous global seeding that would enable a study of both plume and the surrounding entrainment region, and strong laser reflections from the wall surface, which limited the investigation area. I dealt with these issues in the experimentations. In addition to visualization with PIV, I also performed flow visualization with a CMOS video camera. The study provided useful information about the flow pattern over a wall-mounted radiator, and the results from PIV measurements (streamlines) coincided with results from smoke visualization.

Authors' contributions: Sattari conducted the preliminary studies in the field of particle deposition and aerosol technology, designed the measurement room, made the setup, and performed all measurements, analysis, programming, and post-processing. Sattari wrote the main body of the paper, while Sandberg reviewed the article, supervised, and wrote portions of the introduction.

Paper 6

Sattari A (2015) Particle image velocimetry visualization and measurement of air flow over a wall-Mounted radiator (submitted to journal, reviewed, under revision by the author for publication in journal).

This study had a similar experimental setup to that in paper 6, but deeper analysis was performed to study the flow over the radiator. In a radiator-heated room, an air plume formed over the radiator mixes the air and ventilates the room. Turbulent flow compared with laminar one produces greater mixing, and therefore, it is important to identify where the laminar flow over the radiator becomes turbulent. In addition, the rate of particle deposition on wall surfaces above the radiator is related to the gradient of velocity fluctuations near the wall surface.

The velocity vector maps from PIV measurements in this experimental study were properly overlapped, validated, and post-processed using in-house software to provide the average streamlines, and other statistical information, such as standard deviation, average velocity, and covariance of the entire vector field. The results showed that for a typical room, the flow over the radiator becomes agitated after an ordinate of N = 5.00–6.25, in which N is the dimensionless length based on the radiator's thickness. The results of the statistical analysis aligned with PIV visualization and the ordinary video visualization results in paper 5.

Authors' contributions: Sattari did the preliminary studies in the field of particle deposition and aerosol technology, designed the measurement room, made the setup and performed all the measurements, analysis, programing and post-processing. Also, Sattari wrote the paper, which has been submitted to a journal for possible publication. The paper has been reviewed by the journal reviewers and Sattari is revising the article accordingly for publication.

7. References

Adrian RJ (2005) Twenty years of particle image velocimetry. *Experiments in Fluids* 39(2): 159–169.

Airaksienen M, Järnström H, Kovanen K, Viitanen H, and Saarela K (2007, June) Ventilation and building related symptom. Proceedings of Clima WellBeing Indoors, Helsinki, Finland.

Arslanturk C, and Ozguc AF (2006) Optimization of a central-heating radiator. *Applied Energy* 83: 1190–1197.

Bajura RA, and Catalano MR (1975) Transition in a two-dimensional plane wall jet. *Journal of Fluid Mechanics* 70(4): 773–799.

Bajura RA, and Szewczyk AA (1970) Experimental investigation of a laminar two-dimensional plane wall jet. *Physics of Fluids* 13: 1653–1664.

Baldinelli G, and Asdrubali F (2008, December) Reflecting panels for radiators in residential buildings: Theoretical analysis of energy performance. Proceedings of Thermal Issues in Emerging Technologies, ThETA 2, Cairo, Egypt.

Beck SBM, Blakey SG, and Chung MC (2001) The effect of wall emissivity on radiator heat output. *Building Services Engineering Research and Technology* 22(3): 185–194.

Beck SMB, Grinsted SC, Blakey SG, and Worden K (2004) A novel design for panel radiators. *Applied Thermal Engineering* 24: 1291–1300.

Boverket, (2007) *God bebyggd miljö – fördjupad utvärdering av miljömålsarbetet* [*a good built environment – In-depth evaluation of the environmental objectives*]. Karlskrona, Sweden: Boverket. ISBN: 978-91-85751-77-8.

Boverket, (2008) *Regelsamling för byggande* [*Collection of rules and regulations for constructions*] Karlskrona, Sweden: Boverket. Print: ISBN 978-91-86045-03-6, PDF: ISBN 978-91-86045-02-9, ISSN: 1654-8817.

Buchhave P (1992) Particle image velocimetry – status and trends. *Experimental Thermal and Fluid Science* 5(5): 586–604.

Chen F, Yu SCM, and Lai ACK (2006) Modeling particle distribution and deposition in indoor environments with a new drift–flux model. *Atmospheric Environment* 40: 357–367.

Concerted Action EPBD (2015) *Energy Performance of Buildings*, Available at http://www.epbd-ca.eu.

Council of the European Union (2008, December) Energy and Climate Change – Elements of the Final Compromise. Brussels: Council of the European Union.

Dantec Dynamics (2013a) *CCD and SCMOS Cameras*. Accessed 23 January 2015 at http://www.dantecdynamics.com/ccd-and-scmos-cameras.

Dantec Dynamics (2013b) *PSP, Polyamid Seeding Particles*. Accessed 06 May 2015 at https://www.dantecdynamics.com/psp-polyamid-seeding-particles.

Eichler HJ, Eppich B, Fischer J, Güther R, Gurzadyan GG, Hermerschmidt A, Laubereau A, Lopota VA, Mehl O, Vidal CR, Weber H, and Wende B (2005). Laser physics and applications. In: *Landolt-Börnstein Numerical Data and Functional Relationships in Science and Technology, Subvolume A: Laser Fundamentals, Part 1*, H. Weber, G. Herziger, R. Poprawe (ed.). Berlin, Heidelberg, New York: Springer. ISBN3-540-44379-7.

Elsinga GE, Scarano F, Wieneke B, and Van Oudheusden BW (2006) Tomographic particle image velocimetry. *Experiments in Fluids*. 41(6): 933–947.

European Commission, Climate Action. The 2020 Climate and Energy Package. Accessed April 7, 2015 at
http://ec.europa.eu/clima/policies/package/docs/climate_package_en.pdf

European Environment Agency (2006) Energy and Environment in the European Union – Tracking Progress Towards Integration. EEA Report No. 8. Copenhagen: European Environment Agency. ISBN 92-9167-877-5.

European Parliament and the Council of the European Union (2003) Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings. *Official Journal of the European Communities*, 4.1.2003, L 1/65.

Gritzki R, Perschk A, Richter W, and Rösler M (2009) Gekoppelte simulation zur spezifikation von heiz- und kühlkörpern [Combined thermal building simulation for advanced heating and cooling specification]. *Bauphysik* 31(1): 51–55.

Gritzki R, Seidel P, Rösler M, and Felsmann C (2013) Sommerliche raumkühlung im wohnungsbau mittels kombinierter heiz- und kühlsysteme, Teil II – Detailuntersuchungen von heizlcörpern im Kühlbetrieb (Summertime space cooling in residential buildings by combined heating and cooling systems, Part II - Detailed investigations of radiators used for cooling. *Gebäudetechnik and Innenraumklima* 134(3): 174–194. ISSN:2195-643X.

Guha A (1997) A unified Eulerian theory of turbulent deposition to smooth and rough surfaces. *Journal of Aerosol Science* 28: 1517–1537.

Guha A (2008) Transport and deposition of particles in turbulent and laminar flow. *Annual Review of Fluid Mechanics* 40: 311–341.

Hasan A, Kurnitski J, and Jokira K (2009) A combined low temperature water heating system consisting of radiators and floor heating. *Energy and Buildings* 41: 470–479.

Hamdani SE, Limam K, Abadie MO, and Bendou A (2008) Deposition of fine particles on building internal surfaces. *Atmospheric Environment* 42: 8893–8901.

He C, Morawskaa L, and Gilbert D (2005) Particle deposition rates in residential houses. *Atmospheric Environment* 39: 3891–3899.

Hua J, Ouyang Q, Wang Y, Li H, and Zhu Y (2012) A dynamic air supply device used to produce simulated natural wind in an indoor environment. *Building and Environment* 47: 349–356.

Huang L, Ouyang Q, and Zhu Y (2012) Perceptible airflow fluctuation frequency and human thermal response. *Building and Environment* 54: 14–19.

Kandzia C, Schmidt M, and Müller D (2011, June) Room airflow effects applying unsteady boundary conditions. Proceedings of Roomvent International Conference, Trondheim, Norway.

Keil RH, and Baird MHI (1971) Enhancement of heat transfer by flow pulsation. *Industrial & Engineering Chemistry Process Design and Development* 10(4): 473–478.

Kriegel B (1973) Fallströmungen vor abkohlungsflächen in Gebäuden und mögliche Schutzmassnahmen [Down draught from cooled surfaces in buildings and mitigation measures]. unpublished dissertation, Technischen Universität Berlin.

Krzaczek M, and Tejchman J (2012) Indoor air quality and thermal comfort in naturally ventilated low-energy residential houses, In: Air quality - monitoring and modeling, Dr. Sunil Kumar (Ed.), ISBN: 978-953-51- 0161-1, InTech, Available from: http://www.intechopen.com/books/air-quality-monitoring-and-modeling/airquality-in-low-energy-buildings

Lai ACK, and Chen F (2006) Modeling particle deposition and distribution in a chamber with a two-equation Reynolds-averaged Navier–Stokes model. *Aerosol Science* 37: 1770–1780.

Lai ACK, and Nazaroff WW (2005) Supermicron particle deposition from turbulent chamber flow onto smooth and rough vertical surfaces. *Atmospheric Environment* 39: 4893–4900.

Mattsson M, Broström T, Linden E, Lindström S, and Sandberg M (2011) Fan convectors vs. bench heaters in churches – Impact on air velocities. In: Broström T and Nilsen L (eds.) Proceedings of Conference on Energy Efficiency in Historic Buildings Visby, Sweden. ISBN: 978-91-86343-11-8.

McMurry PH, and Rader DJ (1985) Aerosol wall losses in electrically charged chambers. *Aerosol Science and Technology* 4(3): 249–268.

Melling A (1997) Tracer particles and seeding for particle image velocimetry. *Measurement Science and Technology* 8(12): 1406–1416.

Mizeraczyk J, Kocik M, and Podliński J (2007) Flow diagnostics using particle image velocimetry method. In: *Laser Technology VIII: Applications of Lasers, International Society for Optics and Photonics, Proc. of SPIE,* Vol. 6598 65980W1–9.

Myhren JA, Holmberg S (2006, June) Comfort temperatures and operative temperatures in an office with different heating methods. Proceedings of Healthy Buildings Conference Vol. 2: Indoor Climate, Lisbon, Portugal, 47–52.

Myhren JA, Holmberg S (2007a, June) Energy savings and thermal comfort with ventilation radiators – A dynamic heating and ventilation system. Proceedings of Clima WellBeing Indoors Conference, Helsinki, Finland.

Myhren JA, and Holmberg S (2007b) Summertime cooling with ventilation radiators. Proceedings of 6th International Conference on Indoor Air Quality, Ventilation and Energy Conservation in Buildings (IAQVEC): Sustainable Built Environment, Sendai, Japan, 533–538.

Myhren JA, and Holmberg S (2008) Flow patterns and thermal comfort in a room with panel, floor and wall heating. *Energy and Buildings* 40: 524–536.

Myhren JA, Holmberg S (2009) Design considerations with ventilation-radiators: Comparisons to traditional two-panel radiators. *Energy and Buildings* 41: 92–100.

Myhren JA, and Holmberg S (2011) Improving the thermal performance of ventilation radiators – The role of internal convection fins. *International Journal of Thermal Sciences* 50(2): 115–123.

Myhren JA, Holmberg S (2013) Performance evaluation of ventilation radiators. *Applied Thermal Engineering* 51(1–2): 315–324.

Pesavau P, Aksu R, Toprak S, Horvath H, and Seidl S (1999) Dry deposition of particles to building surfaces and soiling. *The Science of the Total Environment* 235: 25–35.

Pio CA, Ramos MM, and Duarte AC (1998) Atmospheric aerosol and soiling of external surfaces in an urban environment. *Atmospheric Environment* 32(11): 1979-1989.

Prasad AK (2000a) Particle image velocimetry *Current Science-Bangalore* 79(1): 51–60.

Prasad AK (2000b) Stereoscopic particle image velocimetry. *Experiments in Fluids* 29(2): 103–116.

Raffel M, Willert CE, Wereley ST, and Kompenhans J (2007) *Particle Image Velocimetry: A Practical Guide,* 2nd edn, Berlin & Heidelberg: Springer-Verlag. ISBN 978-3-540-72307-3.

Riethmuller M, David L, and Lecordier B (2012) Particle image velocimetry. In: *Laser Velocimetry in Fluid Mechanics,* Boutier, A (ed.). Great Britain (London) and the United States (Hoboken): ISTE Ltd and John Wiley & Sons, 159–281. doi: 10.1002/9781118569610

SAFEX®-CHEMIE GMBH (2015) inside-nebelfluid normal/powermix. Accessed 10 March 2015 at http://www.safex.de/safex2/produkte.php?DOC_INST=71

Sandberg M (2007) Whole-field measuring methods in ventilated rooms. *HVAC&R Research* 13(6): 951–970.

Sandberg M, and Elvsén PÅ (2004) Rapid time varying ventilation flow rates as a means of increasing the ventilation efficiency. Proceedings of 9th International Conference on Air Distribution in Rooms, Coimbra, Portugal.

Schiwietz T, Westermann R (2004) GPU-PIV. Proceedings of the Vision, Modeling, and Visualization Workshop, Stanford, CA, 151–158.

Sevilgen G, Kilic M (2011) Numerical analysis of air flow, heat transfer, moisture transport and thermal comfort in a room heated by two-panel radiators. *Energy and Buildings* 43: 137–146.

Shati AKA, Blakey SG, and Beck SBM (2011) The effect of surface roughness and emissivity on radiator output. *Energy and Buildings* 43: 400–406.

Shimada M, Okuyama K, Kousaka Y, Okuyama Y, and Seinfeld JH (1989) Enhancement of brownian and turbulent diffusive deposition of charged aerosol particles in the presence of an electric field. *Journal of Colloid and Interface Science* 128(1): 157–168.

Siegman AE (1986) *Lasers*, the United States, CA: University Science Books, ISBN 0-935702-11-3.

Stanislas M, Kompenhans J, and Westerweel J (2000) *Particle Image Velocimetry – Progress towards Industrial Application*. Location: Publisher. Springer Science+ Business Media Dordrecht, originally published by Kluwer Academic Publishers, 2000; ISBN: 978-90-481-5394-7 (Print) 978-94-017-2543-9 (Online).

Thatcher TL, Lai ACK, Moreno-Jackson R, Sextro RG, and Nazaroff WW (2002) Effects of room furnishings and air speed on particle deposition rates indoors. *Atmospheric Environment* 36: 1811–1819.

Ward IC (1991) Domestic radiators: Performance at lower mass flow rates and lower temperature differentials than those specified in standard performance tests. *Building Services Engineering Research and Technology* 12(3): 87–94.

Wargocki P, Sundell J, Bischof W, Brundrett G, Fanger PO, Gyntelberg F, Hanssen SO, Harrison P, Pickering A, Seppänen O, and Wouters P (2002) Ventilation and health in non-industrial indoor environments: report from a European multidisciplinary scientific consensus meeting (EUROVEN). *Indoor Air* 12(2): 113–128.

Wargocki P, Wyon DP, Sundell J, Clausen G, and Fanger PO (2000) The effects of outdoor air supply rate in an office on perceived air quality, sick building syndrome (SBS) symptoms and productivity. Proceedings of Indoor Air;10 pp222–36.

Westerweel J (1997) Fundamentals of digital particle image velocimetry. Measurement science and technology8: 1379–1392.

Westerweel J, Elsinga GE, and Adrian RJ (2013) Particle image velocimetry for complex and turbulent flows. *Annual Review of Fluid Mechanics* 45: 409–436.

Wigö H, and Knez I (2005) Psychological impact of air velocity variations in ventilated room. *Ergonomics* 48(9): 1086-1096.

Xia Y, Zhao R, and Xu W (2000) Human thermal sensation to air movement frequency: Air distribution in rooms. Proceedings of Roomvent International Conference, Reading, UK, 41–46.

Xu M, Nematollahi M, Sextro RG, Gadgil AJ, and Nazaroff WW (1994) Deposition of tobacco smoke particles in a low ventilation room. *Aerosol Science and Technology* 20(2): 194–206.

Zhao B, and Wu J (2007) Particle deposition in indoor environments: Analysis of influencing factors. *Journal of Hazardous Materials* 147: 439–448.

Zygo Corporation (2015) Surface Measurement, Accessed 28 April 2015 at http://www.zygo.com/?/met/profilers/surfacemeasurement.htm.