Further Investigation of the Convective Heat Transfer between Rooms through Open Doorways

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Abstract
Bidirectional flows through open doorway proved to be an important process to distribute heat inside buildings. In the context of super-insulated buildings, the space-heating distribution can be simplified so that each room is not systematically equipped with a heat emitter. To assess the resulting thermal comfort, the amount of heat flowing through open doorways should be predicted accurately. Bidirectional flows through doorways have been widely investigated in the scientific literature. Nevertheless, two important aspects remain unclear. Firstly, the conditions where the boundary-layer and bulk flow regimes are dominant are still not well defined. It is here proved using Computational Fluid Dynamics (CFD) that the bulk flow regime may be active on a larger range than previously reported. Previous investigations most often neglected thermal radiation while it is here shown that this physical effect is important. Secondly, the measured temperature profiles appear to be smoother than predicted by the theory or CFD, affecting the real amount of heat convected through the doorway. In theory, this smoothing can be explained by two-dimensional effects not considered by classic models or by mixing between the two counterflows. Unfortunately, experiments were not able to confirm these hypotheses. In conclusion, the present work tends to prove that additional research is needed in this area in order to design robust simplified distribution systems, or to interpret results from ventilation network approaches in building performance simulations.

Keywords - airflow; doorway; passive house; heat distribution; simplification

1. Introduction
The necessity to drastically reduce the space-heating (SH) needs of residential buildings in Europe has prompted the emergence of building concepts based on a super-insulated building envelope, such as the passive house (PH) standard. Given the level of insulation and the use of high-performance windows, the SH distribution system can be simplified in these buildings because it is theoretically not necessary anymore to place a heat emitter in each room, or in front of windows. A well-known simplification is
the so-called centralized air heating but one could also consider a wood stove or a limited number of low-temperature radiators [1]. In practice, there is lack of fundamental knowledge to support the simplification of SH distribution systems in PH. In fact, the limitation of the heat emitters’ number to a couple of rooms inevitably leads to temperature differences with the other “non-heated” rooms. In order to reach an acceptable thermal comfort in the entire building, the heat transfer between rooms should be promoted. Different studies have however shown that the opening of internal doors is an efficient way to homogenize temperature in PH. In fact, a large bidirectional flow will occur through doorways with flow rates that are significantly higher than the nominal hygienic airflow rates provided by the balanced mechanical ventilation [2]. The present study aims at investigating how this convective heat exchange can be properly predicted. Results can be used to design simplified SH distribution systems in PH, especially for cold climates.

The flow assessment using building performance simulation (BPS) most often relies on a ventilation-network model [3, 4] (e.g. the COMIS software). Airflows through doors are then essentially modeled using a large opening approximation which introduces the concept of discharge coefficient, Cd, to tune the model to specific flow physics [2].

1. Hypotheses behind this model (i.e. “bulk-flow”, isothermal rooms) are unfortunately crude so that it could not be directly applied to the present application: the heat emitter can have a relatively higher surface temperature than the room.

2. Furthermore, the temperature field within the doorway may differ significantly from this theory. Consequently, the convective heat exchange is different than expected.

These phenomena have not been reported extensively in the scientific literature. Consequently, the present contribution will report on these two limitations using Computational Fluid Dynamic (CFD) and laboratory measurements.

2. Transition between flow regimes

The flow through open doorways has been investigated extensively by the scientific community, mainly about two decades ago, see e.g. [2]. These investigations were essentially based on measurements. The performance of CFD was also tested for this type of flow but on rather crude meshes (i.e. some thousands of nodes). Measurements already confirmed the two possible flow regimes. Taking one warm and one cold room connected by an open doorway, the boundary layer regime is characterized by a small temperature difference between the bulk air temperature of both rooms (dT) and a large temperature difference between the heating and cooling walls (DT). Defining the isothermal factor θ as the ratio of dT/DT, the boundary layer regime is characterized by a θ near zero [5]. According to Scott et al.
[5], this regime appears when the wall temperature are relatively high and when the boundary layer can flow freely through the doorway without being blocked. The blockage effect was then investigated by reducing the width of the doorway compared to the width of the room. For example, the boundary layer regime occurs when the doorway is as large as the room or in a two-dimensional flow (2D). The second regime is the bulk flow or density-driven regime. In this case, the difference between the wall and bulk air temperature is relatively small. On the contrary, the flow is driven by the difference of hydrostatic pressure between the two rooms, this pressure difference being generated by a difference of bulk air temperature dT. In other words, the isothermal factor θ is close to unity for bulk flows. This type of flow is assumed in most building simulation softwares, see e.g. [6, 7]. Due to the complexity of the bidirectional flow, it is impossible to arrive to a general solution covering all the physical parameters of the problem. The bidirectional flow in the doorway is then rather evaluated using a simplified model assuming strictly horizontal and inviscid flows. The corrections for viscous effects, or bi- and three-dimensional flows, are introduced with a phenomenological factor, the discharge coefficient, Cd [8].

In case of space-heating where the heater surface temperature can be relatively high, it is difficult to predict a priori the type of flow regime that takes place. In previous investigations from the authors, the airflow through a doorway has been measured in a Norwegian passive house in Trondheim using different heat emission systems as well as using different heater locations in the warm room [9]. The velocity appeared in good accordance with the bulk flow approximation. The Cd showed to be almost independent of the heater type and location. Nevertheless, understanding transition between boundary-layer and bulk flow is important as it will determine the final temperature difference between the rooms. In past investigations, the transition has been essentially investigated in terms of change of room and aperture widths [5, 10-12]. Nevertheless, it has been concluded in IEA EBC Annex 20 that further research was needed in this area. In particular, these investigations have been made with a limited amount of thermal radiation between walls, either using water as a medium [5, 12], or air but using walls covered by aluminium [10, 11]. The present contribution aims at proving that thermal radiation is an important factor to explain the transition between the two flow regimes.

3. Transition analysis using CFD

The impact of the door width and thermal radiation is investigated using CFD for generic a geometry, see Figure 1. The advantage of CFD is that boundary conditions are well controlled and that thermal radiation can be turned “on” and “off” easily. In addition, the computational power has significantly increased the last two decades so that meshes with millions of points can be used.
The two rooms have a depth of 4m and height of 3m. In the baseline case, the warm room has a width \((W)\) of 7m, while this dimension is reduced to 3m in order to investigate narrow rooms. The cold room is always 7m. The open doorway is located in the middle of the partition wall, with a height of 2m and a width \((w)\) of 1m. A constant and uniform heat flux of 300W is imposed to a surface of 3m² in the warm room, while a constant and uniform temperature of 0°C is imposed to one wall in the cold room. All other walls are considered adiabatic. The emissivity of walls \(\varepsilon\) is set at 0.8, except for the radiator and the cold wall where it is set to 0.0. The baseline geometry is meshed with ~3 million tetrahedra with boundary layer meshes along surfaces. RANS simulations have been performed using ANSYS® Fluent. The \(k-\varepsilon\) RNG model has been used with full buoyancy effect and standard wall functions (maximum \(y^+\) is ~10). Given the high Rayleigh number, the solution is converged using a second-order spatial discretization and a real time stepping (so-called URANS) as recommended by Fluent for buoyancy-driven flows. The solution is assumed converged when heat emitted by the radiator (300W) is exactly equal to the heat absorbed by the cold wall and the total heat crossing the doorway. In addition, the relative residual for mass conservation should be lower than 1e-3 after each time iteration. When activated, the thermal radiation exchange is computed using the S2S model.

Fig. 1 Sketch of the generic geometry: two rooms connected by an open doorway.

Both temperature profiles and velocity profiles are shown here to illustrate the transition between flow regimes. They are taken along lines in the middle of the doorway and 2m in front of the doorway in the middle of both rooms. From Figure 2, the narrow room \((w/W = 1/3)\) without radiation clearly appears to be in the boundary layer regime. Firstly, stratification is large in the warm room with a hot air layer located on the top part of the room (above 1.5m height). This temperature is large because walls are adiabatic and no physical process like thermal radiation redistributes the heat downwards in the entire room. This warm air needs to flow only on the top
part of the doorway to convect 300W. This leads to a velocity profile which is asymmetric, see Figure 3. Secondly, the air temperature below 1.5m are equal between both rooms ($\theta \sim 0$).

Taking the large room without radiation the flow regime stays in the boundary layer regime as reported by Scott et al. [5] for this level of aperture width ratio ($w/W = 1/7$). Nevertheless, if thermal radiation is activated, it clearly triggers the bulk flow regime. Firstly, the velocity profile starts to be almost symmetric and parabolic, with a neutral plane located slightly above the middle of the doorway, see Figure 3. Secondly, one clearly notices that the vertical stratification is reduced in the warm room due to homogenization effect of radiation. This effect slightly neutralizes the hot layer in the warm room so that a larger airflow is needed to convect the 300W radiator heat through the doorway. A temperature difference ($dT$) appears between both rooms and $\theta$ is no longer equal to zero.

For the narrow room with radiation, the behavior is intermediate between a boundary layer and a bulk flow regimes. These results tend to prove that one should be more careful when specifying the conditions for transition. Firstly, it was reported in [2, 5, 10] that the door width should at least be $\sim 10\%$ of the room width to ensure the flow to be in the boundary layer regime (and thus limiting the temperature difference between rooms).
The present results show that the bulk flow regime can be dominant well above these \( \sim 10\% \). In other words, one may state that the bulk flow regime could have a range of applicability which is larger than previously expected. Secondly, one should be careful in the interpretation of experiments where radiation is neglected (e.g. in water). Thirdly, the homogenization process proposed here is the thermal radiation. Nevertheless, other physical processes may be present in reality, such as downwards boundary layers along walls when these are not adiabatic. Finally, building simulation softwares generally only consider the bulk flow regime while the narrow room case \( (w/W = 1/3) \) clearly shows that it is not fully valid. In addition, most building models assume isothermal rooms so that one may wonder whether the computed flow makes sense for these narrow rooms. These results are not definitive and deserve to be validated and extended, but they show that further investigations are needed in this area.

![Velocity profile for the four simulation cases: with the baseline or the narrow warm room, with and without the thermal radiation activated.](image)

Fig. 3  Velocity profile for the four simulation cases: with the baseline or the narrow warm room, with and without the thermal radiation activated.

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4. **Measured temperature field in the doorway**

The temperature field in the doorway is further discussed here as it is of major importance for the convective heat transfer. The RANS simulation with the large room and radiation shows a temperature profile that is good accordance with theory. Below the neutral plane, the air temperature in the doorway equals the cold room temperature at the same height, while, above the neutral plane, the air temperature is equal to warm room temperature at the same height. The transition between both temperature levels is sharp and located near the neutral plane.

Nevertheless, past experiments in a Norwegian passive house have not shown a similar temperature distribution, even though the velocity field was in good accordance with the bulk-flow theory [13]. Therefore, further investigations were performed in the NTNU laboratory in order to better measure this temperature field [14-16]. The configuration of the experiments
was different than using the CFD, see Figure 4. Two electric panel heaters of 600W each were installed in the back of the warm room. They were equipped with a thermostat with a dead band of 0.5-1K. The cold room was left unheated and, being in contact with rest of the large laboratory premises, it undergoes a relatively small temperature change when heating was applied. The flow in the doorway was measured using ten omni-directional anemometers TSI 8475 (accuracy ± 3% ± 0.005m/s) placed along one vertical pole in the middle of the door. Twenty PT-100 sensors (accuracy ± 0.1K) were used to measure the air temperature: 10 in combination with the anemometers within the doorway and 2x5 anemometers placed on two vertical poles that measured the temperature stratification in each room. By default, these two bars were located 2m away from the doorway, see Figure 5 (from [14]).

Fig. 4 Sketch of the laboratory geometry.

Fig. 5 Sketch of the measurements point in the warm room (right) and cold room (left): red points correspond to PT-100 temperature sensors and green point to anemometers.
The measurements results of Paul Minard [15] are shown here but other investigations at NTNU showed similar results [14, 16]. The warm room was heated during 3 hours to a set-point temperature of 26°C, with the mechanical ventilation system turned off. After this startup period, the vertical bars in both rooms have been moved from 2m from the doorway, to 1.5m, 1.0m and 0.5m by steps of 10 minutes. Data was sampled every 20 seconds and averaged over a 10 minute period. Results are reported on Figure 6 [15]. The velocity shows that the flow is rather symmetric meaning that it should be in the bulk-flow regime even though the room is narrow. One can clearly notice that the temperature in the doorway is well smoother than predicted by the theory. The transition between the cold and room temperature occur over a large vertical distance, especially above the neutral plane where ~0.7m is necessary for the doorway temperature to equal to the warm room temperature at the same height. As this temperature profile departs from the theory, the convective heat exchange between both rooms is well different than expected.

Fig. 6 Measured velocity and temperature profiles: 2m from doorway (plain lines), 1.5m (dash-dotted lines), 1.0m (dotted lines), 0.5m (dashed lines), warm room (red), doorway (black) and cold room (blue).

Two hypotheses can be proposed to explain this phenomenon. Firstly, the theory assumed that the flow is horizontal so that it is consistent to compare the temperature in the doorway and in both rooms at an equivalent height. In practice, the flow is not one-dimensional but two-dimensional (2D). According to Etheridge and Sandberg [8], a difference of height between the doorway and the rooms generates these 2D effects. To answer this question, the bars have been progressively moved towards the doorway as previously explained. From Figure 6, one can notice that this 2D effect can be seen but it cannot explain the temperature profile in the doorway (at least up to a distance of 0.5m from the doorway). Secondly, the smoothing of the temperature profile may be explained by some mixing occurring in the middle of the doorway. Somehow, heat should have been exchanged between the cold and the warm streams to generate such a smooth profile.
The only article we found in the literature reporting about this phenomenon is the article of Wilson and Kiel [17] where they indeed showed that interfacial mixing between the two streams typically smoothes the temperature profile and reduces the velocity in the doorway. In addition, Etheridge and Sandberg [8] briefly mentioned that 2D effects may trigger mixing. Further investigations have been performed in the laboratory to detect this phenomenon using smoke visualization [16]. Nevertheless, this approach appeared unsuccessful due to the very-low velocity in the middle of the doorway (i.e. < 0.1m/s). In conclusion, the nature of the temperature profile should be explained by either 2D effects or interfacial mixing (or a combination of the two). Nevertheless, measurements were not accurate enough to make conclusions possible; a higher resolution in space and time is needed. This knowledge is required to accurately predict the actual convective heat exchange between rooms.

5. Conclusions

The bidirectional flow through an open doorway has been here investigated. Two physical phenomena are important for the design of simplified space-heating distribution. Firstly, the transition between boundary layer and bulk flow regimes has been investigated using CFD (here RANS). Previous works reported that the aperture width ratio was the main driving parameter to detect this transition (due to the blockage effect). The present CFD investigations prove that the thermal radiation strongly influences this effect and that the bulk flow may still be dominant for large door widths. Secondly, the measured temperature profiles within the doorway are smoother than predicted by the theory. CFD using RANS was not able to reproduce this effect. Two hypotheses have been proposed to explain this effect: two-dimensional flow and mixing between the air streams. Unfortunately, laboratory measurements were not able to detect whether these effects explain the temperature smoothing. More detailed measurements in space and time are required. The understanding of this behavior is needed to well predict the convective heat transfer between rooms. The mass transfer already proved to be well reproduced by theory.

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