Room Airflow Measurements in a Simplified Geometry

Summary

Because people spend most of their time indoors, it is important to learn more about thermal comfort and to get more information about different room air flow structures depending on isothermal and non-isothermal boundary conditions.

Numerical calculations on the one hand and experimental investigations on the other hand can be used to analyze the room air flow. The role of the numerical calculations is becoming increasingly important. Hence, it is necessary to validate these calculations using high quality experimental data.

Detailed measurements are carried out in a realistic model room, the Aachen model room (AMoR). Depending on the introduction of the supply air and the thermal loads different types of room air flow structures occur in the AMoR. The measurement results of the speed and the temperature, including isothermal and non-isothermal boundary conditions as well as high and low inlet velocities, are presented for several measurement heights and planes. These results will be used as benchmark for room air flows.

Introduction

People spend more than 90% of their life indoors (Sprengler, 1983). Therefore it is necessary to create an environment in which people feel comfortable. One focus in this context is the air conditioning in rooms. The air flow structures in a room are transient, three dimensional and turbulent. Each room air flow structure is unstable and characterized by different kinds of large eddies. The size, lifetime and shape of these eddies in a room air flow depends on the boundary conditions (Moog, 1981). Even if a large number of different studies has been done, further investigations are necessary to learn more about the behavior of room air flow structures. Next to the experimental investigations the simulations of room air flows are getting more important (Nielsen, 2014). The use of flow simulations requires the validation of the calculation programs.

The Aachen model room (AMoR) shows an idealized case of a typical ventilation situation like in a meeting room, a plain or a train cabin. The supply air is introduced close to the ceiling and the heat sources are positioned on the floor. The exhaust air leaves the model room at the bottom zone. The measurement results of the Aachen model room will be used as benchmark for room air flows.

The idea behind the benchmark test is to provide the measurement data of an experimental investigation at different boundary conditions of the supply air as well as the thermal loads. It can be used as validation of the results of different methods of computational fluid dynamics. Further, the results of different investigations can be compared with each other.

The Aachen Model Room (AMoR)

Due to its construction the model room can provide the basic air flow phenomena of forced convection in the upper part of the room due to the supply air jets and free convection at the walls of the heat sources. The model room (see Figure 1) is 5 m long, 4 m wide and 3 m high. The walls are made of wooden plates (10 mm) and polyurethane plates (80 mm). The supply air is introduced into the model room directly below the ceiling. The slot diffusers are installed over the whole length of the room on both sides. Every supply air inlet is 0.02 m high and one meter long. A volume flow controller in front of each supply air inlet enables a variation of the supply air velocity in between 0.5 m/s and 5 m/s. The outlet air leaves the model room at the bottom zone. The exhaust openings are 0.15 m high.

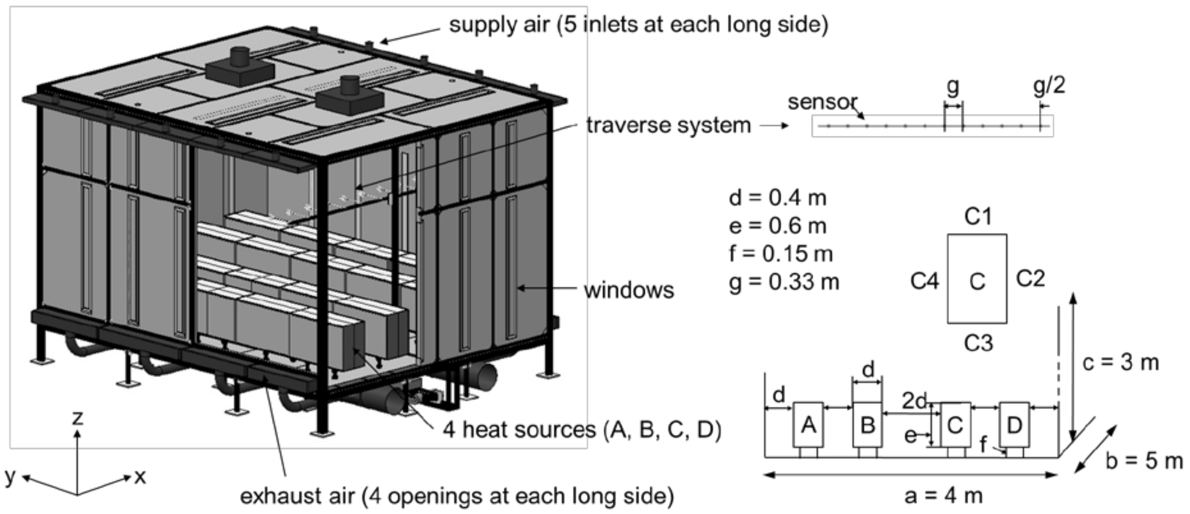

Figure 1: Aachen model room – AmoR

The thermal loads inside the model room are realized by four electrically heated cuboids. The heat sources are 5.0 m long, 0.4 m wide and 0.6 m high. The cuboids are constructed by aluminum plates which are pasted with heating foils. Insulation inside the heat sources avoids an internal thermal layering. Each aluminum plate is 1 m long. Hence, the four heat sources are constructed of 80 segments. In the middle of each segment the surface temperature is measured. The heat sources are mounted on 0.15 m high feet. All geometry information of the model room is shown in figure 1. To minimize the radiation heat transfer all walls of the model room are laminated with an aluminum foil.

Measurement types in the model room

The temperature of the supply air and the exhaust air as well as the temperature field inside the room is measured by platinum resistance thermometers. The velocity field in the room is measured with the aid of omnidirectional anemometers. The output of the sensors is the speed of the local velocity vector. The measuring range of the probes for the air speed is between 0.05 and 5 m/s, with an accuracy of 0.05% as specified by the manufacturer (sensor.electronics.pl, 2014).

The sensors are positioned automatically in the model room by using a traverse system. Twelve sensors (speed and temperature) are fixed at the traverse system. The distance between two sensors is 0.33 m (see Figure 1). The distance between the wall and the first sensor is 0.17 m. A motor enables a movement to almost every point of the model room, and another motor to every level above the heat sources up to a height of 2.7 m. The area between the heat sources is not measured. Because of the deflection pulley it is not possible to measure the area in the model room which is higher than 2.7 m. Hence, the velocity distribution of the supply jet is not measured. The measurement types and numbers of sensors of the experimental investigations are given in Table 1.

Table 1: Measurements in the model room and the number of sensors

measurement type	**number of sensors**
speed	12
room air temperature	12
surface temperature (heat source)	80
supply air temperature	10
exhaust air temperature	8

Flow structures in the AMoR

Different boundary condition cause different room air flow structures. Based on measurements in the whole model room (Kandzia, 2013) a simplified representation of the air flow structures is shown in the following. In all cases the supply air as well as the thermal heating loads are introduced over the whole length of the model room. The supply air is introduced either from both sides or from only one side of the model room.

If the supply air is introduced into the model room under isothermal conditions, two large and stable eddies are formed. The supply air jets are bounded to the ceiling until both jets collide and unify to one transient jet structure yielding downwards to the occupied zone. Above the heat sources, the jet is separated and deflected to the sides of the model room. At the side walls of the model room, the flow is directed upwards to the ceiling and is finally induced by the supply air. The two stable eddies occupy the entire space between the heat sources and the ceiling. The lowest velocities are to find in the middle of the two large eddies. The room air flow structure is nearly two-dimensional over the whole length of the model room (see Figure 2, left).

In the case of non-isothermal boundary conditions and inlet velocities greater than 2 m/s, the two large eddies are moving closer to the ceiling because of the buoyancy forces of the heat sources (see Figure 2, center). At lower inlet velocities, the room air flow structure is disordered and unstable. The upper part of the model room is dominated by the forced convection of the supply air and the part directly above the heat sources is dominated by free convection (see Figure 2, right). The structure of the flow is three-dimensional.

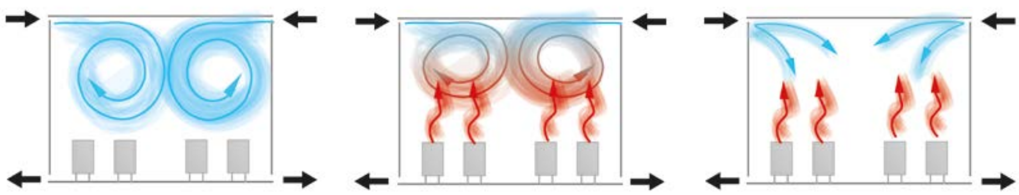

Figure 2: Air flow structures (supply air from both sides), left: isothermal, center: mixed convection wherein the forced convection is dominant, right: mixed convection, wherein neither of the two forces is dominant

In the case of the one-sided air supply and isothermal boundary conditions one large eddy structure is formed. The supply air jet bounded at the ceiling until it reaches the opposite wall of the model room. The jet is yielding downwards to the occupied zone and passes above the heat sources to the wall side of the supply air diffusers. At this side wall, the flow is directed upwards to the ceiling. Like in the case of two large eddies, the lowest velocities are to find in the middle of the large eddy and the room airflow structure is nearly two-dimensional over the whole length of the model room (see Figure 3, left). In the case of inlet velocities up to 2 m/s the large eddy does not fill up the whole width of model room.

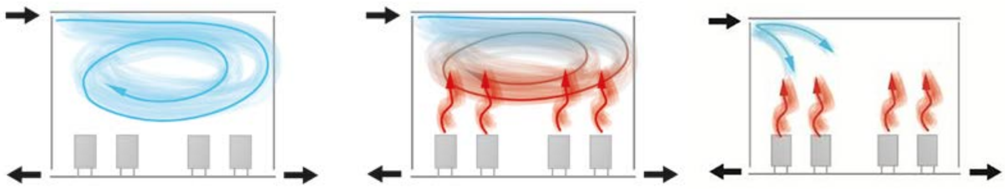

Figure 3: Air flow structures (supply air from one side), left: isothermal, center: mixed convection wherein the forced convection is dominant, right: mixed convection, wherein neither of the two forces is dominant

In the case of non-isothermal boundary conditions, the large eddy is moving closer to the ceiling like in the case of two large eddies (see Figure 3, center). Lower inlet velocities cause an unstable room air flow structure. The upper part of the model room is dominated by the forced convection of the supply air. The lower part is influenced by the free convection of the heat sources (see Figure 3, right).

Boundary conditions of the experimental investigations

The experimental investigations in the Aachen model room are done under isothermal and non-isothermal boundary conditions. The supply air is introduced into the model room either from both (BS) or from only one long side (OS). Table 2 gives an overview about the different experimental investigations.

Table 2: Boundary conditions of the experimental investigation

Introduction of the supply air	BS	BS	BS	BS	BS	BS	BS	OS	OS	OS
$v_{supply\ air}$ in m/s	2	3	4	1	2	3	4	3	1	3
Q in kW	0	0	0	2	2	2	2	0	1	1

The measurements are done in 11 planes and 6 heights in the model room. Figure 4 shows the different measurement points for the experimental investigations. The measurement time at each point was ten minutes (Kandzia, 2013).

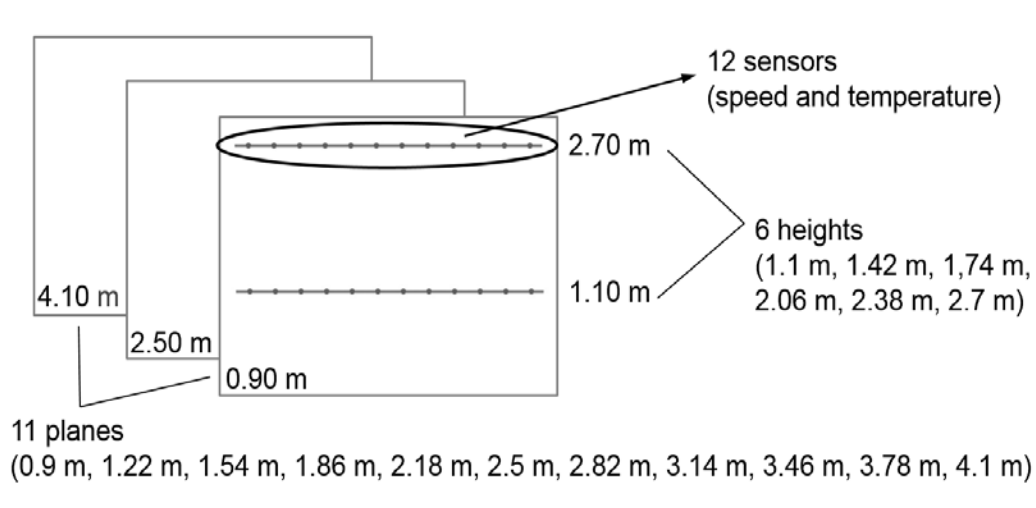

Figure 4: Measurement planes and heights in the Aachen model room

The measurement data of the experimental investigations (see table 2) are saved in two different Excel sheets separated in isothermal (AMoR _isothermal.xlsx) and non-isothermal boundary conditions (AMoR_non_isothermal.xlsx). Next to this point one Excel sheet presents the measurement data of the room air flow at different positions of the exhaust opening (AMoR_exhaust.xlsx). Each Excel sheet includes detailed information about the measurement positions and the boundary conditions of the experimental investigation.

The Excel sheets include the mean values of the different measurement types (see table 1), the standard deviation and the turbulence intensity at each measuring point in the model room. In the case of the supply air as well as the exhaust air temperature only one mean value of the temperature is given every ten minutes. The Excel sheets can be downloaded from the following homepage:
https://www.ebc.eonerc.rwth-aachen.de/go/id/ewyq/lidx/1/

Exemplary presentation of the results of one experimental investigation

To get a first idea how to read the measurement data, a simplified presentation of the results of one experimental investigation is given in a separated Excel sheet (AMoR_example_instationary). The inlet velocity at each supply air inlet was 1.5 m/s and heating loads of 2 kW were introduced equally into the model room. The measurements were done in only three different planes (0.9, 2.5 and 4.1 m) and three different heights (1.1, 1.9 and 2.7 m). Hence, the structure of the measured values is much easier to understand. The measurement points are shown in Figure 5.

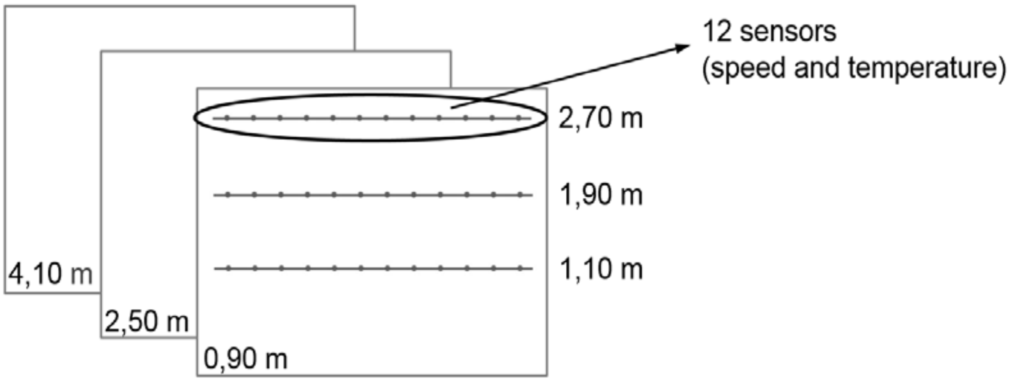

Figure 5: Measurement planes and heights for the simplified presentation of the results

Next to the speed, the standard deviation and the turbulence intensity are calculated at each measuring point in the model room. The measurement types and the number of mean values which are given in the Excel sheets are shown in Table 3.

Table 3: Data in the Excel sheets

measurement type	**number of mean values**
speed	12
standard deviation	12
turbulence intensity	12
room air temperature	12
surface temperature (heat source)	80
supply air temperature	1
exhaust air temperature	1

The presentation of the measurement results for speed, standard deviation turbulence intensity and room air temperature are given in the same way. The results for the speed are exemplarily represented in Table 4. The first column shows the plane, the second column shows the height and the next twelve columns show the mean values of the respective measurement type. The mean values are calculated for the measurement duration of ten minutes.

Table 4: Exemplary presentation of the measurement results for the speed

plane	**height**	**1**	**…**	**12**
0.9	1.1	0.1673		0.1613
	1.9	0.2129		0.2444
	2.7	0.1783		0.1791
2.5	1.1	0.1744		0.1717
	1.9	0.1988		0.2083
	2.7	0.1616		0.1684
4.1	1.1	0.1764		0.1721
	1.9	0.1380		0.1193
	2.7	0.1824		0.1974

As shown in Figure 6 the four heat sources are labelled with A, B, C and D (see Figure 6, right). From the front to the back the plates are numbered from 1 to 5.

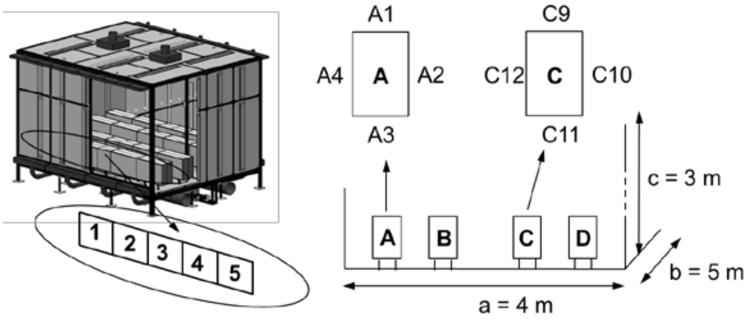

Figure 6: Geometry information of the heat sources

Table 5 shows how the surface temperatures of the heat sources are presented in the benchmark file. Again one value is given as mean value of all measurement values of the measurement duration of ten minutes. The results are exemplary shown for heat source C.

Table 5: Presentation of the measurement results for the surface temperatures of the heat sources

plane	height	C-1,1	…	C-4,5
0.9	1.1	33.4381		38.4591
	1.9	33.4763		38.4722
	2.7	33.4824		38.4838
2.5	1.1	33.4138		38.5585
	1.9	33.4758		38.5578
	2.7	33.4439		38.5688
4.1	1.1	33.4868		38.7011
	1.9	33.4605		38.7099
	2.7	33.4421		38.7160

Presentation of the measurement results

The measurement results for the mean speed, the mean turbulence intensity and the mean room air temperature are presented in the following three figures (Figure 7 to Figure 9). Each figure includes three diagrams for the three different measurement planes (0.9 m, 2.5 m and 4.1 m). Each diagram shows three lines. The blue line corresponds to a measurement height of 1.1 m, the green line to a height of 1.9 m and finally the red line corresponds to a measurement height of 2.7 m. The 12 dots in each line represent the measurement position of the sensors. The distribution of the mean speed is shown in Figure 7.

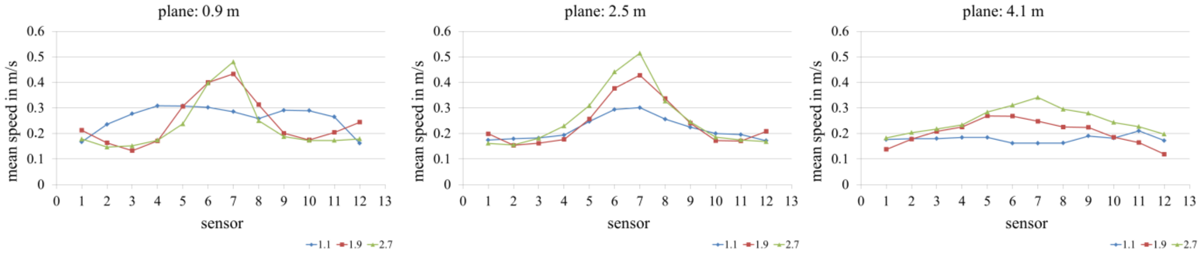

Figure 7: Mean values of the speed in the model room for three measurement planes at inlet velocities of 1.5 m/s and thermal loads of 2 kW

It is not possible to specify a representative two dimensional flow for the three different measurement levels. The mean speeds vary at different levels. The flow structure is three dimensional. In the first level (0.9 m) the values of the mean speeds represent a stable room air flow structure. The highest speeds in the middle of the room in a height of 1.9 m and a height of 2.7 m represent the jet which is yielding downwards to the occupied zone. The speed is about 0.5 m/s. The lowest values of the mean speeds represent the centers of the two large eddies. In a measurement height of 1.1 m the speeds at the side walls of the model room show the lowest values. The influence of the heat sources cause higher values in the middle of the model room. The mean speeds in the middle of the model room (2.5 m) are considerably less distinctive. The flow structure in the upper part of the model room is influenced by forced convection. In the lower part of the model room, the influence of free convection is dominant. The third measurement plane (4.1 m) shows no representative speeds of the large and stable eddies as found in the first plane (0.9 m). Neither the highest speeds in the middle of the model room nor the lowest speeds in the center of the two large eddies can be found in the measurements heights 1.9 m and 2.7 m. Rather, the values of the mean speeds show a similar distribution in all three measurement heights. The highest measurement height shows the largest mean values of the speed.

The curves of the mean values of the turbulence intensity (see Figure 8) show exactly the opposite behavior to the distribution of the mean speed. Particularly low speeds correspond with particularly high values of the turbulence intensity. Hence, the highest values of the turbulence intensity of up to 60 % can be found in the first measurement plane (0.9 m) in a measurement plane of 1.9 m. These measurement points represent the center of the large and stable eddies.

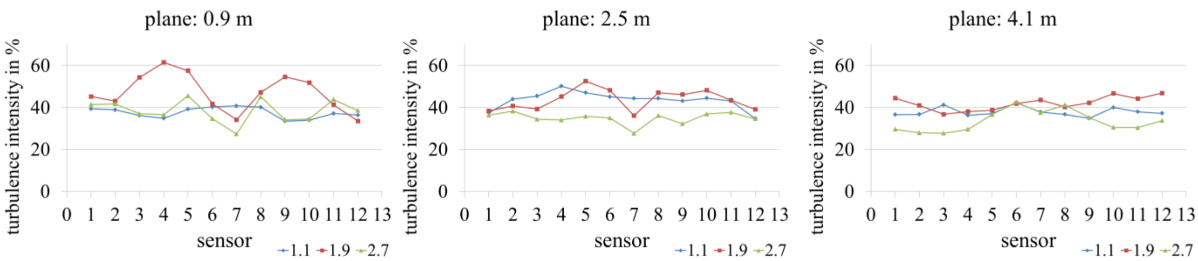

Figure 8: Mean values of the turbulence intensities in the model room for three measurement planes at inlet velocities of 1.5 m/s and thermal loads of 2 kW

Figure 9 shows the measurement results for the room air temperature. Like the distribution of the turbulence intensity the curves of the mean room air temperature show the opposite behavior to the curves of the mean speed. The highest temperatures with values of 26.5 °C are found in the lowest measurement height (1.1 m) in the third measurement plane (4.1 m).

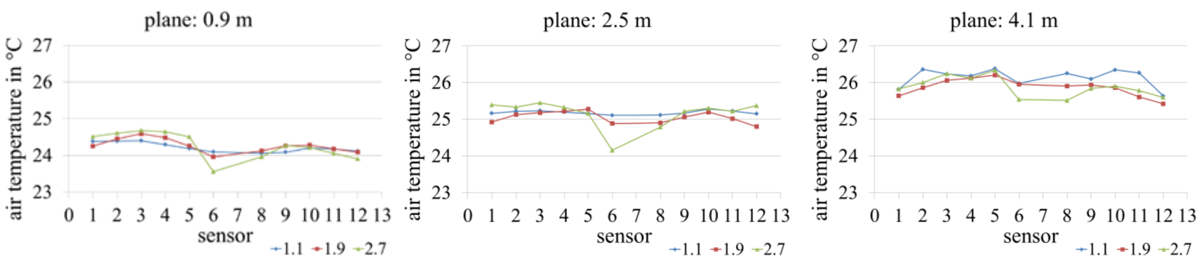

Figure 9: Mean values of the room air temperature in the model room for three measurement planes at inlet velocities of 1.5 m/s and thermal loads of 2 kW

Due to the two-dimensional geometry of the model room, a uniform surface temperature of the heat sources has to be expected over the whole length of the model room. Especially in the case of an unstable room air flow structure this is definitely not the case. Figure 10 shows the surface temperatures of the heat source C. The values do not represent a mean value of the measurement duration of ten minutes but a mean value of the duration of the whole experimental investigation.

As shown in Figure 6 the plates of the four heat sources are numbered from 1 to 4. The blue line in Figure 10 (C1) represents the results of the mean surface temperatures of the upper parts of the heat source. Because of the influence of the forced convection of the supply air these surface temperatures show the lowest values. In contrast, the surface temperatures of the other parts of the heat source show higher values. Furthermore, the mean surface temperatures increase from sensor number 1 to sensor number 5. Compared with the results of the mean speeds (see Figure 7) the lowest values of the surface temperatures correspond with the highest values of the mean speed. An increase of the surface temperature of the heat source appears together with an increase of the room air temperature (see Figure 9).

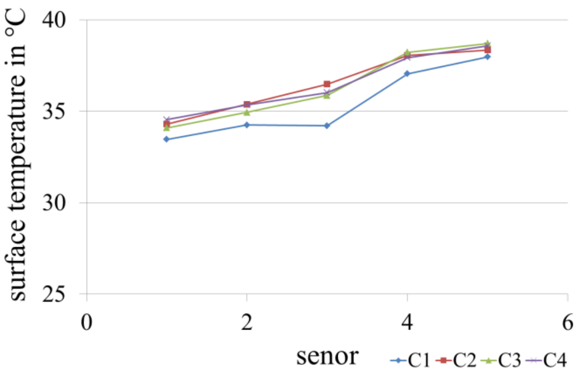

Figure 10: Mean values of the surface temperatures of heat source C

Comments to the experimental investigation to the Influence of the position of exhaust air openings

These comments relate only to the Excel file: AmoR_exhaust.xlsx.

In general, it is assumed that the flow structures depend on the location and momentum flow of the supply air inlets. Considerably less attention is paid to the position of the exhaust air openings. In contrast to the supply air opening, less momentum is introduced into the room at the exhaust air opening. Therefore, the long-range effect is considerably weaker. The local low pressure region close to the exhaust air opening causes an acceleration of the flow. The velocity decreases with the square of the distance from the exhaust air opening. Hence, a direct influence of the flow is only recognisable in the direct vicinity of the opening (Baturin, 1953).

The experimental investigations are carried out on five levels (0.9 m, 1.7 m, 2.5 m, 3.3 m and 4.1 m) and at three heights (1.1 m, 1.9 m and 2.7 m). The measurement duration in each case is ten minutes. The different positions of the exhaust air openings are shown in Figure 11. The figure shows the top view of the model room. The arrows symbolize the position of the exhaust air opening in each case. In the first case (a.) the air is discharged on both sides over the whole length of the model room. In the second case (b.) the air leaves the model room on only one long side of the model room, in the third case (c.) at the back part of the model room and finally in the last case (d.), all of the exhaust air is discharged on one side in the back part of the model room.

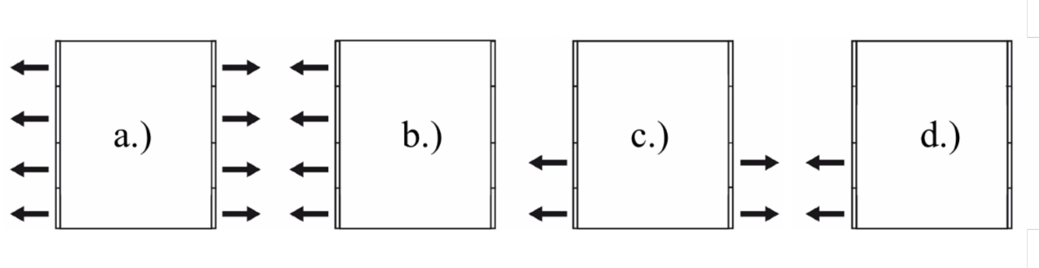

Figure 11: Top view of the model room with the different positions (indicated by arrows) of the exhaust air opening

The model room can be disassemble at a reasonable effort in its individual parts. The wall construction is therefore planned with a minimum amount of subareas. The windows for the optical measurement processes as well as an easily-handled size of the plywood are responsible for not identical wall segments. Associated with this the exhaust openings do not have the same length. To guarantee an even discharge of the room air they are also provided with volume flow controllers. The length of the exhaust openings is given in Figure 12.

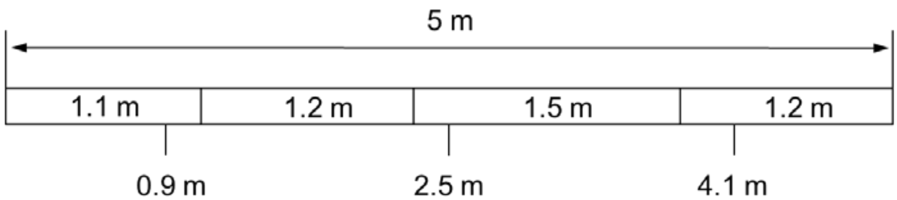

Figure 12: Length of the exhaust air openings

The volume flow which is introduced into the model room on both sides at a supply air velocity of 1.5 m/s, is the maximum flow possible that can be removed on the side of exhaust in case d.). The first measurement is done under isothermal boundary conditions and inlet velocities of 1.5 m/s (both sides). Inlet velocities of 1.5 m/s (both sides) and thermal loads of 2 kW cause an unstable room air flow structure. Hence, this case is the second step of the experimental investigation. A detailed description of the measurement results is given in [15].

Conclusion

Detailed experimental investigations under isothermal and non-isothermal boundary conditions are done in the Aachen model room. The measurement results will be used as room air flow benchmarks. The representation of the measurement results is done in different tables for the mean speed, the standard deviation, the turbulence intensity and the room air temperature in the model room. Next to these data the results for the supply and exhaust air as well as the surface temperature of the heat sources are also given.

The measurement duration of the experimental investigation was ten minutes at each measurement point. The mean values at each measuring point are published.

Acknowledgement

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