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The impact of the Human Body's Convective Boundary Layers on the Design of a Personalized Ventilation Diffuser

Vliv mezních vrstev lidského těla na návrh vyústky pro osobní větrání

The paper deals with the specifications of a settable range of air volumes for a personalized ventilation system to provide an appropriate fresh air supply to the user. It mainly deals with the interaction of fresh air flow and human convective boundary layers and the difference in various volumes and velocities. Measurement of the flow interaction was taken by a Particle Image Velocimetry (PIV), using a thermal manikin to simulate the environment around the human body.

Keywords: *diffuser, personalised ventilation, PIV, convective boundary layers*

Článek se zabývá vhodným zvolením rozsahu možného nastavení objemu přiváděného vzduchu pro personalizované větrání, aby bylo dosaženo vhodné distribuce k uživateli. Primárně se tak potýká s interakcí přiváděného vzduchu s konvektivními mezními vrstvami okolo lidského těla s proudem přiváděného vzduchu při různých objemech a tedy i rychlostech. Měření vzájemné interakce proudění bylo prováděno metodou Particle Image Velocimetry, za použití termálního manekýna k simulaci prostředí okolo lidského těla.

Klíčová slova: *vyústka, osobní větrání, PIV, konvekční hraniční vrstvy*

INTRODUCTION

Personalized ventilation is one of the modern alternatives to solve efficient air distribution and to create a pleasant microenvironment in offices and any other fixed workspace [1] [6]. The efficiency lies in distribution of the fresh air direct to the user by personalized local diffusers, which are mostly mounted on the table. It sounds simple, but there are many influences in the local place, which can dramatically decrease the effect of the personalized ventilation. One of those things is the user himself, specifically the user's body. The human body produces metabolic heat and this heat is emitted to the surrounding air. The temperature gradient between this heated air and the surroundings creates a convective upward airflow around the body [2] [3] [4]. The velocity and impact of these convective boundary layers depend on the temperature difference between the body and the environment. The convective boundary layers are capable of carrying many pollutants created by the human body to the person's breathing zone, and those pollutants can negatively impact the perceived air quality [2].

Figure 1 Convective boundary layers around the sitting human body.

It has been proven that convective boundary layers interact with the ventilation system [2] [5] and especially with personalised diffusers [3]. The study of the interaction between personalised ventilation and human convective boundary layers [3] shows that the real impact of personalised ventilation can be quite different due to the boundary layers. In the mentioned study of personalised ventilation, only 30 % of the supplied fresh air reached the user's breathing zone, when the boundary layers were fully developed. On the contrary, when the boundary layers were broken by a movable table panel or air intake, the effectivity of the inhaled air increased to 90 %.

In our task, we designed personal ventilation diffusers for use in a workspace of air traffic dispatcher. The air flow rate is manually controlled by the user, but according to the previous mentioned studies, there are flow rates with absolutely inefficient velocities, which would not even reach the user and can be even less effective than mixed ventilation. On the contrary, high velocities are efficient, but may become really uncomfortable over longer use.

The main task of this measurement was the range of the controller that we should use to make our system both comfortable and efficient for the user.

PROTOTYPE MEASUREMENT

To measure the diffuser and boundary layers flow interaction, we used a Particle Image Velocimetry (PIV) system. This system uses fast capturing cameras to track small particles diffused in the air. To specify the measured particles, a laser layer is used to light up the particles. From the captured images, it is able to calculate the exact velocity vectors of the airflow.

To study the interaction, we divided the measurement into three parts. The first measurement was focused on the airflow of the selected diffuser. The second one measured the velocities of the convective boundary layers around the body of the thermal manikin and the third combined the two previous ones to measure the interaction between them. We measured three different flow rates, which means three different velocities at the diffuser.

PIV setting
For our measurement, we used oil bubbles with a size of 100 – 1000 nm as tracing particles. The particles were equally dispersed in the room's air without any supplementary flow and they were dispersed in the supply air in the measurements of the diffusor.

For the diffusor and manikin measurement, only one camera was used. But to capture the flow interaction, we used two cameras next to each other to increase the measured area.

The calculation of the average velocities was made from fifty continually captured images.

The room ventilation system was turned off to provide steady air conditions. The air temperature was set to 23 °C with a deviation up to 0.5 K. The measured ambient air velocity in steady conditions was in the range from 0.03 to 0.12 m/s. Measurements were made for isothermal flow, it means that the temperature of the supply air was the same as the temperature of the ambient air.

Thermal manikin setting
Because convective boundary layers depend on the temperature gradient, they are different with each different kind of clothing. From our research questionnaire, we approximated some standard clothing that the dispatcher's wear at work and we used that to simulate some standard situation in the office. We used a long-sleeved shirt and trousers to set the thermal insulation value to 0.54 clo.

The manikin was set to a standard surface temperature of 35 °C. The manikin was not breathing in order to measure the average speed around the breathing zone without the velocity of the breath.

The diffuser measurement
At first, we just measured the diffuser to get the main information about the flow. We measured both the vertical and horizontal plane. The diffuser was mounted to the table as it should be in the real situation. The supply air had the same temperature as the environment.

The size of the diffuser is 50 x 300 mm and is set in a vertical position, 140 mm above the table plane. It is divided by 5 partitions on the vertical plane and there are 9 lamellae to shape flow on the horizontal plane. The size is based on the conditions of the dispatcher's workspace, which are quite limited, and to provide 25 m^3/s with an average velocity of 0.2 m/s in the diffuser plane. We used 25 m^3/s of supply air for the measurement of the flow according to actual legislature.

We can easily notice the partitions on the vertical plane. However, it forms one united flow after a distance of 350 mm. The flow forms cylinder with higher velocities in its core. The core is about 270 mm above the table, which is planned to correspond with the height of the upper part of the chest bone of the sitting user. Dispersion in the vertical plane is higher than in the horizontal one, which is not the effect we hoped for, but it was given by the size of the diffuser.

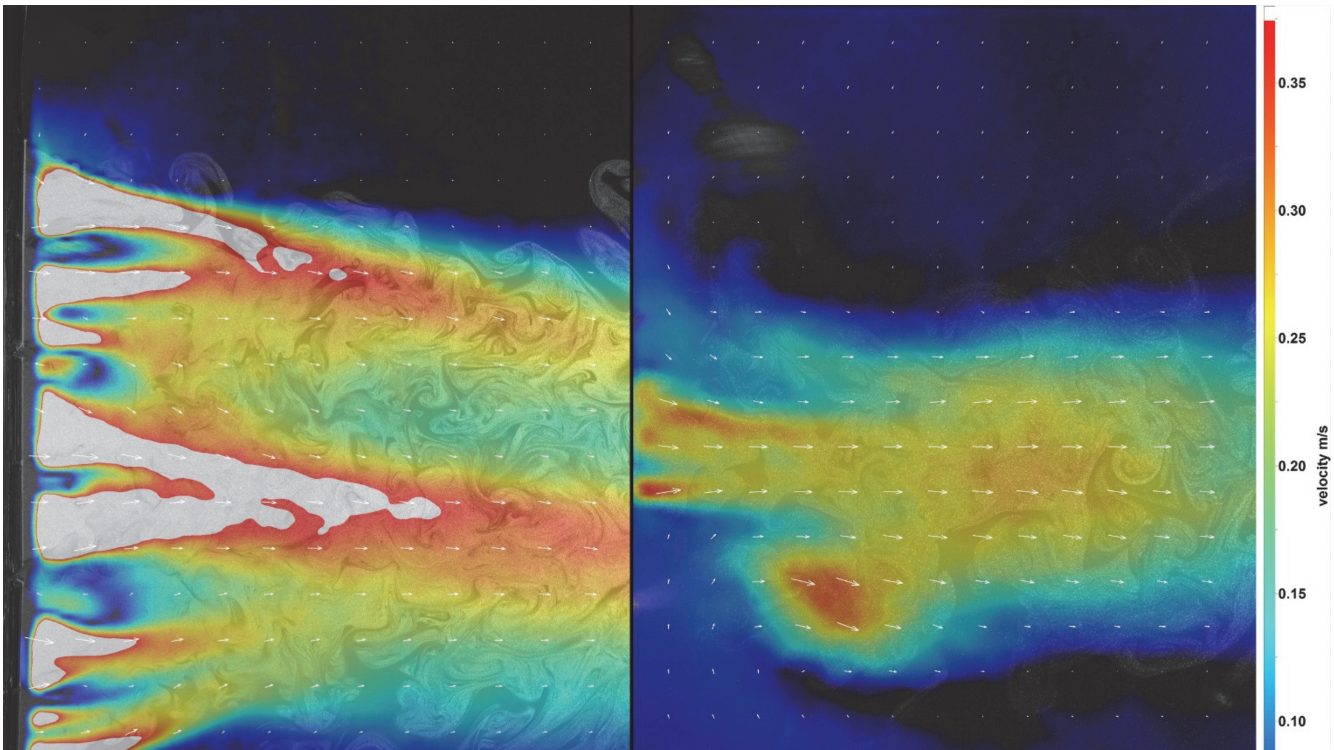

Figure 2 PIV vertical (left) and horizontal (right) vector field of the diffuser

Measurement of the convective boundary layers
The second measurement was focused on the boundary layers around the body. To simulate the human body, we used a thermal manikin to reach its steady state when the diffuser is turned off. The results of the measurement are shown in Figure 3.

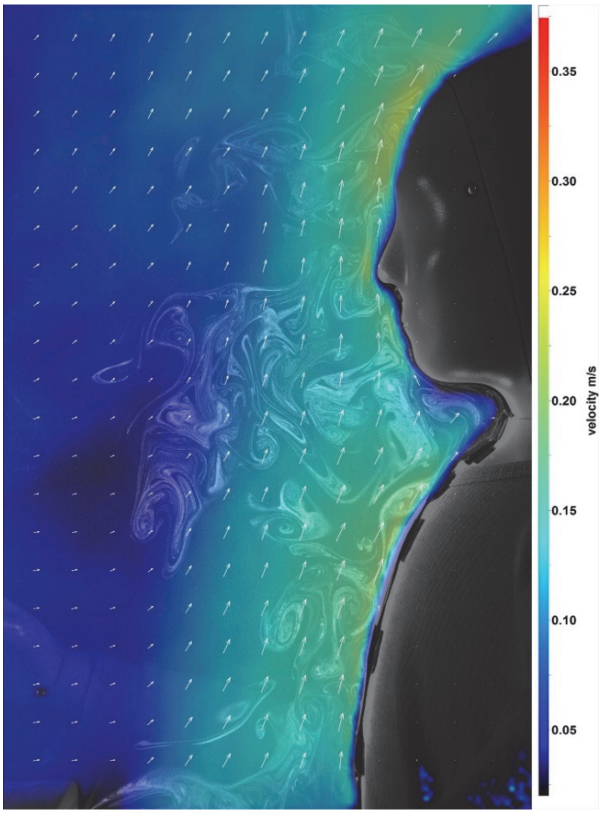

Figure 3 Vector field of the boundary layers

We can see the upward flow of the boundary layers around the manikin. The velocity range is from 0.1 m/s to 0.25 m/s and the width of the layer is about 100 mm at the height of the chest and about 70 mm at the height of the head. The fastest flow is around the large surfaces, like the chest, and around the head of the manikin. Also, the hands have their own influence, but it is only partially involved in the measured layer.

The figure shows the impact of the boundary layers to our comfort and environment. In steady air conditions, we mainly breathe the air that came from around our feet. When it reaches the breathing zone, it is already polluted by body odours and pollutants.

Measurement of the flow interaction
The third measurement combines two previous ones. We measured the thermal manikin and the diffuser together to measure the interaction of those two flows. The manikin and diffuser were set to the same settings as before.

The diffuser was in front of the manikin at a distance of 950 mm from the manikin's body. The laser layer was set from behind the diffuser in order to exactly measure the flow around the body. The settings of the measurement are shown in Figure 4. The measured plane captures the distance of 600 mm in front of the manikin.

We divided the measurement into parts with different speeds, to find out which speed is sufficient to penetrate the layers. Three different air flow volumes were used: 15 m³/h, 25 m³/h and 30 m³/h, parallel to the average velocities 0.12 m/s, 0.2 m/s, and 0.24 m/s in the plane of the diffuser. From the previous testing, we assumed that the first flow rate will not be sufficient to penetrate the boundary layers, the second should one be, but with limited efficiency, and the third should be the most efficient, but on the edge of comfortable use.

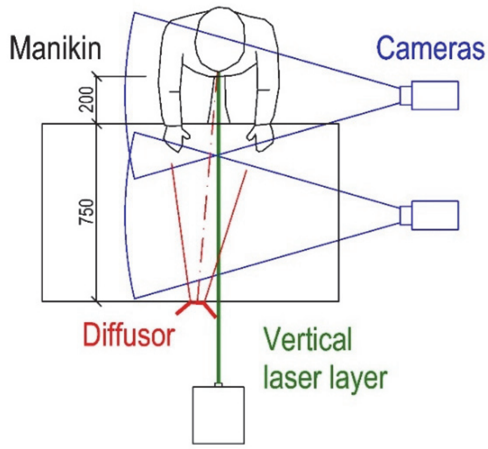

Figure 4 Settings of the flow interaction measurement

The lowest flow rate (of 15 m³/h) results are shown in Figure 5. We can see that the core is reaching a maximum velocity of 0.18 m/s at the maximum measured distance (600 mm from the manikin), but it decreases toward the manikin. At the distance of 220 mm (the gap between the pictures), the flow is almost scattered and has almost no influence on the boundary layers. Most of the fresh air just moved upward with the boundary flow and the effect of the ventilation with these velocities is marginal for the user.

We can see better results in Figure 6, where the results of the second flow rate of 25 m³/h are shown. The velocity in the core is higher, about 28 m/s, and it makes a real difference. The airflow from the diffuser is combined and mixed with the air transported by the boundary layers in the breathing zone. That means a user will partially breathe fresh air and partially breathe the polluted air transported by the upward flow. However, the boundary layers still have a great influence on the air in the breathing zone.

In the third situation, the flow rate of 30 m³/s, we can see a difference. The results of the measurement in Figure 7 show how the higher velocities affect the flow around the body.

The core velocity is up to 0.38 m/s and the flow reaches the manikin in the velocity of 0.25 m/s at the upper chest and neck. But there is a real difference in how it affects the boundary layers. In the previous measurements, the main source of heat was the chest and head, but in this situation, the airflow from the diffuser cools those surfaces and lowers the temperature difference. Then the body generates a weaker upward flow, which causes the supply air not to flow upwards, as in previous situation, but it goes around the neck behind the manikin (This effect was also measured with radiant cooling panels [2]). Both effects have a real impact on the effectivity of personalized ventilation, because most of the fresh air now reaches the breathing zone. We can say that increasing the air volume by 5 m³/h has a much greater positive effect.

On the other hand, it can have a negative impact on the personal temperature comfort, because it cools the sensitive parts of the body, like the neck and upper torso.

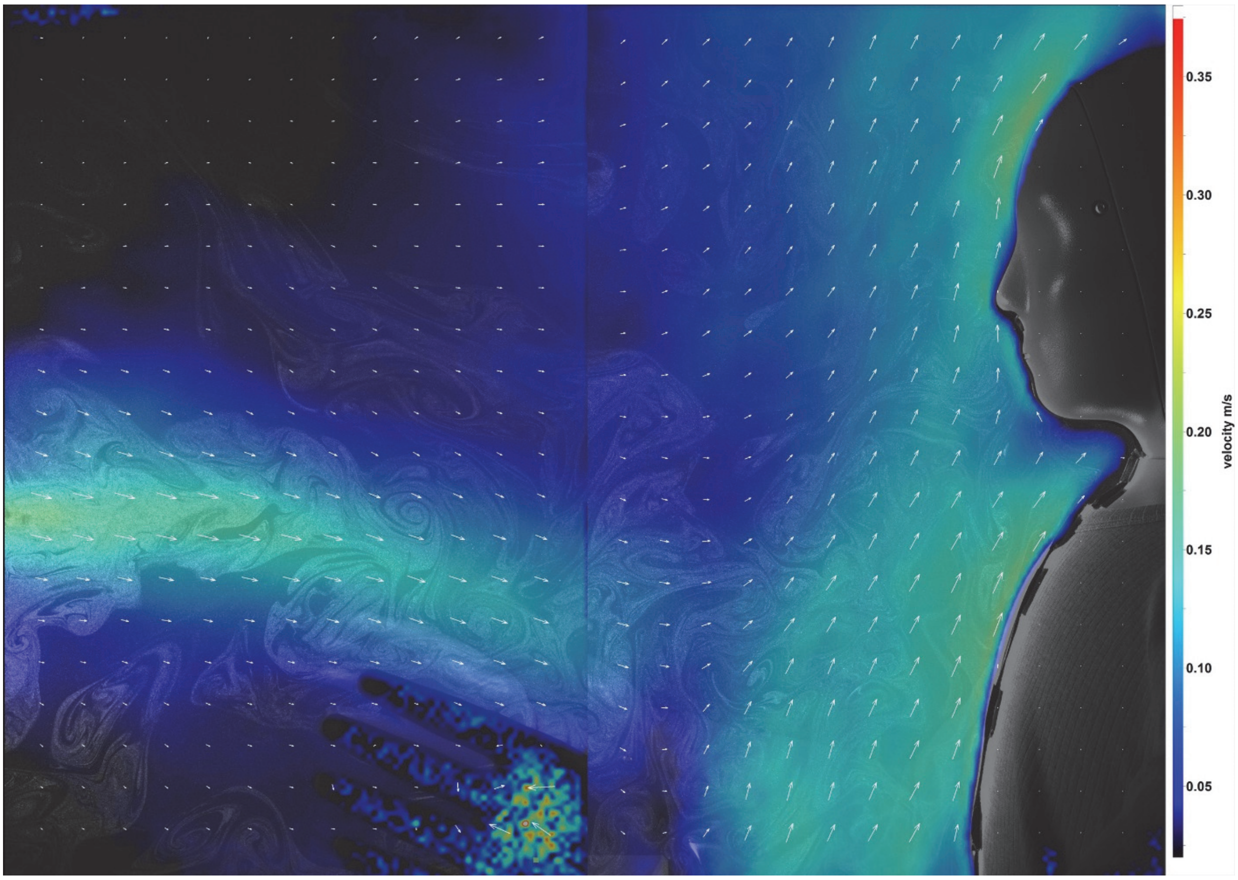

Figure 5 Interaction of the flows with a supply of 15 m³/h

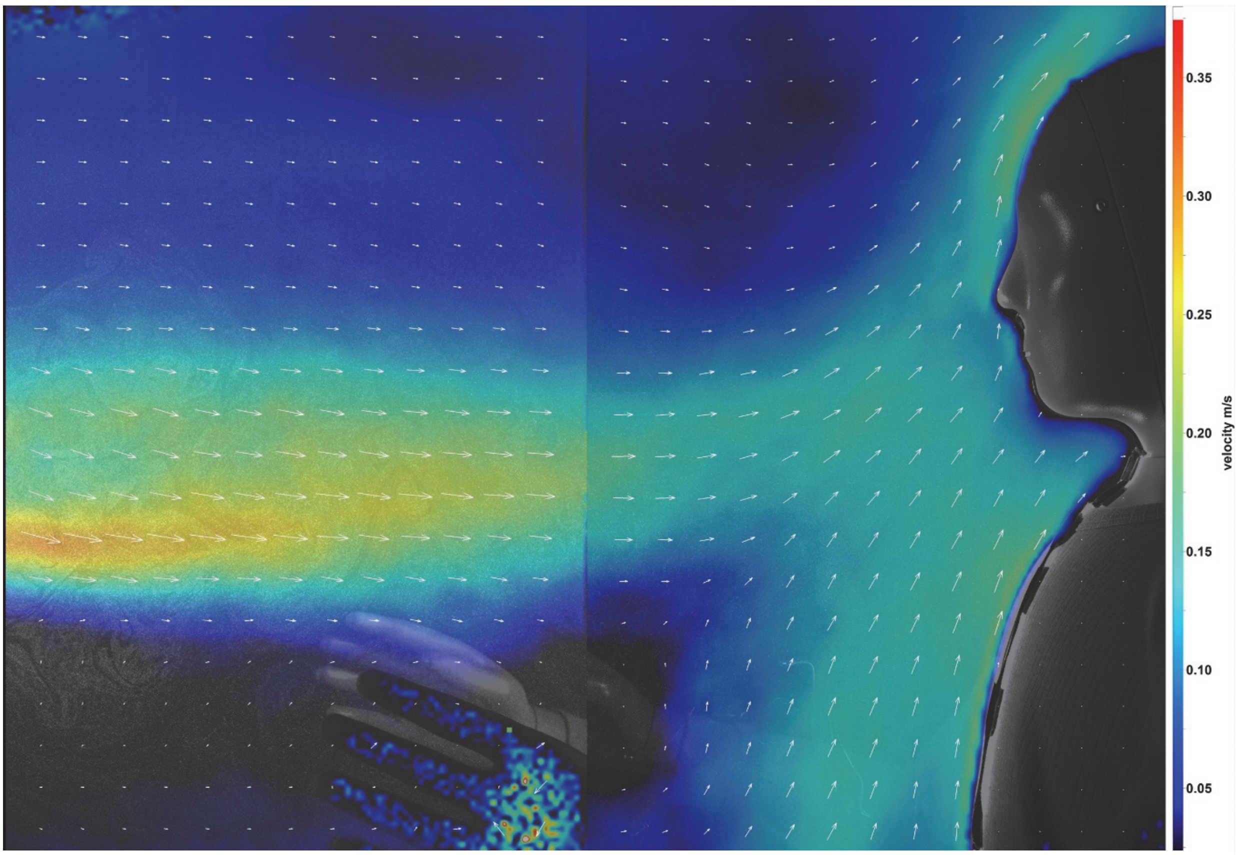

Figure 6 Interaction of the flows with a supply of 25 m³/h

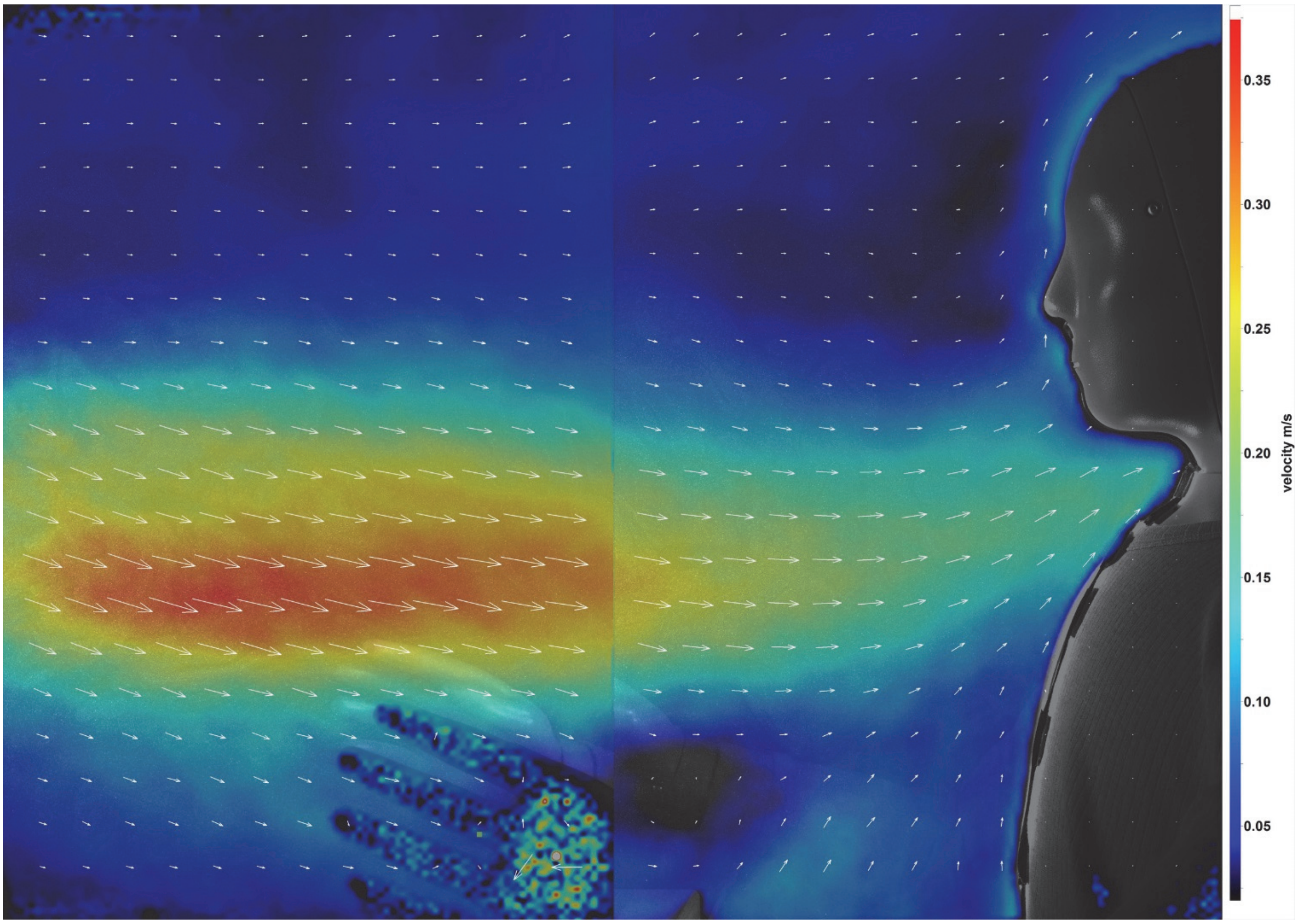

Figure 7 Interaction of the flows with a supply of 30 m^3/h

CONCLUSION

We measured three different flow rates to get information about what range we should choose to personalise the flow rate. We can say from the results that the lower limit for the controller should be around 20-22 m3/h, where the ventilation starts to have a positive effect to the user. The upper limit should be set to around 30 m^3/s, where it is already around the maximum efficiency. However, the upper limit is not only dependent on measured effectivity itself. The upper limit should be more exactly determined by the thermal comfort of the user. In the next study, we should use a thermal manikin to measure the influence of higher velocities on the body's temperature to set the point more exactly.

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