Air-jet cover for heat treatment chamber

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Abstract. To increase the efficiency of local exhaust hoods for removing harmful substances emitted during technological processes, air is supplied by jets to create an air curtain (air-jet covers). The air curtain prevents the spread of harmful substances, does not interfere with the technological process, and leaves the equipment open for control and monitoring. The device of local supply and exhaust ventilation of the open doorway of the UKM Classic M 2005 chamber made by Mauting is considered. The chamber is designed for heat treatment of meat products in the food industry. Geometric models have been developed, including a heat treatment chamber, a room from which the chamber is loaded, a supply and exhaust hood above the door from the chamber to the room, and a supply air duct with air distribution devices. For comparison, an option of using an exhaust hood without supply air was also studied. The STAR-CCM+ software package was used as a calculation program. The results of computational experiments on modeling the operation of the local ventilation system of the heat treatment chamber are presented. The analysis of the calculation results and comparison of the efficiency of local ventilation devices are carried out. The studied design of the supply and exhaust hood ensures that heat and gases coming out of the heat treatment chamber are captured at a 17% lower supply and exhaust air flow rate compared to the exhaust hood.

1 Introduction
Local exhaust hoods are used to capture harmful substances released during technological processes [1-6]. Studies of local exhaust hoods of various types are described in articles [2, 3], where the values of the capture coefficient (efficiency of catching harmful substances) are also given. Based on the performed analysis of the main publications describing different types of local exhaust hoods, it is shown that their efficiency depends on the design, aerodynamic and operating parameters.

Local exhaust hoods of an open-type are widely used in industry. For example, hoods, lateral, side and ring exhaust units. To increase efficiency, the exhaust devices are activated by the supply jets. The air jet, which prevents the spread of harmful substances, does not interfere with the technological process and leaves the equipment open for control and observation. Studies have shown that, if properly organized, the “supply jet - exhaust device” system is more effective than open hoods. Such a system provides a more reliable trapping of emitted harmful substances with significantly lower volumes of exhaust air.

Devices with a jet of air acting as a screen are called air-jet covers (AJC). This screen prevents the penetration of harmful substances from the “dirty” area into the “clean” one. Examples of air-jet covers are given in [4].

Unlike free turbulent jets, AJC jets develop in difficult conditions. On the one hand, there is a vast...
room space, on the other - a limited localized space. These conditions affect jet formation and exhaustion efficiency. The purpose of this study is to assess the effect of the design and pattern of air supply of an air-jet cover on the efficiency of local exhaust hoods.

Heat treatment chambers used in many branches of industry were adopted for the study. Chambers have different purposes and technical characteristics. However, their design and principle of operation are unchanged and the results of the study can be generalized for equipment used for various technological purposes.

2 Materials and Methods
This study examines the operation of local exhaust hoods from the opening of the UKM Classic M 2005 chamber made by Mauting [7] intended for heat treatment of meat products in the food industry. The layout of the heat treatment chamber is shown in Figure 1.

![Figure 1. UKM Classic M 2005 chamber.](image)

According to the manufacturer of the UKM Classic M 2005 heat treatment chamber [7], the following characteristics are accepted:
- chamber opening with width \( a = 1.87 \, \text{m} \), height \( b = 2.30 \, \text{m} \);
- chamber length is \( 5.3 \, \text{m} \);
- height of the hood attachment from the axis of the chamber doorway - \( H = 1.15 \, \text{m} \);
- temperature of the gas-air mixture inside the chamber - \( t_g = 60 \, ^\circ\text{C} \);
- air temperature in the room - \( t_r = 18 \, ^\circ\text{C} \).

The area of the room into which the chamber doorway opens is a working area related to this heat treatment chamber. Site dimensions: height - 4.6 m, length - 3.87 m, width - 4 m.

A geometrical model has been developed (Figure 2), including: a heat treatment chamber; the room from which the camera is loaded; exhaust (supply and exhaust) hood over the door from the chamber to the room; supply air duct with air distribution devices.

In the SolidWorks software, two versions of the models of the heat treatment chamber were created with exhaust and supply devices, and with a section of the room adjacent to the chamber (Figure 2):
- a model with an exhaust hood above the chamber doorway and an inflow organized into the side zones of the room (option 1). An exhaust hood (0.8 m wide, 1.87 m long, with an exhaust air duct of 400 mm in diameter) is used as a local ventilation device, adjacent to the upper border of the chamber doorway;
- a model with a supply and exhaust hood (air-jet cover) above the chamber doorway and an inflow organized into the side zones of the room (option 2). The supply and exhaust hood is based on the design of the KV F supply and exhaust hood made by Halton [8, 9] (Figure 3).
The design of the supply and exhaust hood of the KVF model is based on a system of horizontal and vertical nozzles located on the lower and lateral (inner) sides of the hood, which increases the efficiency of localizing air flows over the kitchen equipment. On the bottom of the front side of the hood, there are supply air distributors that create concentrated jets to supply air from top to bottom. Air is removed through exhaust holes 4 (Figure 3). To remove the same amount of excess heat in such a system, the exhaust air flow rate is 30-40% less compared to a traditional exhaust hood.

To compensate for the exhaust, air is supplied into the room through the supply air duct with two 400×300 mm openings located at the edges of the room at a height of 3.75 m. The exhaust through the hood is fully compensated by the supply.

The STAR-CCM+ software package is used as a calculation program.

Modeling the process of operation of local exhaust ventilation from the heat treatment chamber is divided into 2 stages:
- the first stage - modeling the operation of supply and exhaust ventilation in the area of the room with the closed door of the heat treatment chamber is carried out before establishing a stationary mode in the room; this stage is intermediate before the main one;
- the second stage (main) - modeling the work of local exhaust hood from the chamber doorway. It begins after the end of the first stage, simultaneously with opening the door to the heat treatment chamber and combining the volumes of the room and the chamber, continues until the removal of heat and gas emissions escaping through the chamber doorway into the room.

a) option 1 - with an exhaust hood
b) option 2 - with a supply and exhaust hood

**Figure 2.** Geometric models of the heat treatment chamber. 1 - supply openings; 2 - hood; 3 - heat treatment chamber; 4 - room; 5 - supply and exhaust hood (air-jet cover).

The model has the following assumptions:
- adiabatic conditions on the surfaces of enclosing structures, heat treatment chamber, supply air duct and hood;
- components with insignificant concentration were excluded from the gas composition of the chamber and the following mass fractions of the mixture components were taken: water vapor 1.01%, dry air 98.79%, carbon monoxide (CO) 0.01%, carbon dioxide (CO2) 0.19%;
- gas mixture - ideal incompressible gas, mixture components do not enter into chemical reactions.

In numerical modeling, the equations of motion (Navier-Stokes), the equation of continuity and the equation of heat transfer [10, 11] were used. To take into account the turbulent nature of the movement of the medium, the k-ε-model of turbulence is used. Non-stationary implicit method of calculation is used.
Figure 3. Supply and exhaust hood [8, 9]. 1 - supply air distributors; 2 - air nozzles; 3 - air supply; 4 - air removal.
The numerical experiment provides for the control of temperature and air velocity. At the second stage, after opening the door to the heat treatment chamber, the air velocity and the temperature of the gas-air mixture in the model volume are controlled. The control is carried out using real-time display of velocity and temperature fields in the characteristic sections of the model shown in Figure 4. The fields of velocities and temperatures display information that allows evaluating the efficiency of the local exhaust device in the required and sufficient volume.

At the zero moment of time, a stationary air flow regime is established in the room in front of the heat treatment chamber, there are no disturbing influences inside the chamber, and the door to the chamber is closed.

Modeling the operation of the supply and exhaust hood begins from the moment the door to the heat treatment chamber is opened and the volume of the chamber is combined with the volume of the room.

Figure 4. Typical sections of the model. 1 - vertical section; 2 - horizontal section.
3 Results

Option 1. Calculations were made for the model with air supply inlets located at the edges of the serviced room, and with air flow rates removed by the exhaust hood - 3800, 5400, and 7500 m$^3$/h.

With the exhaust air flow rate of 5400 m$^3$/h, 10 seconds after opening the chamber door, the air-gas mixture exits the heat treatment chamber through an open doorway in its upper zone. Hot air does not break through the edge of the hood.

After 20, 30 and 55 seconds, there is a slight overflow of the boundary layer of air into the room from the boundary of gaseous media between the room and the chamber (Figure 5). This overflow is a mixture of hot gas-air mixture of the chamber and cold air of the room, with a significant predominance of the latter. The temperature of this flow does not exceed 20 °C. The gas-air mixture of the chamber is completely removed by the exhaust hood. No breakthrough of the hot gas-air mixture of the heat treatment chamber through the edge of the exhaust hood is observed.

At 75 seconds after opening the chamber door to the room, the removal of the gas-air mixture from the heat treatment chamber is completed (Figure 6).

Option 2. For models with a supply and exhaust hood, the flow rates of the removed and supplied air are taken in accordance with the recommendations [7, 9]. The calculations were made for two exhaust air flow rates - 3000 and 4500 m$^3$/h. Below are the data of the most effective options.

Option 2.1 - supply and exhaust hood; supply air flow rate in the room is 3780 m$^3$/h; supply air flow rate in the supply and exhaust hood through the holes for concentrated supply is 720 m$^3$/h; exhaust air flow rate is 4500 m$^3$/h.

10 seconds after opening the chamber door, the gas-air mixture exits the heat treatment chamber through the open doorway in its upper zone. The supply jets of the supply and exhaust hood are deflected relative to the vertical axis towards the chamber doorway. The distribution of temperatures in the zone of replacement of the gas-air mixture of the chamber with supplied air indicates intensive mixing and heat and mass transfer processes.

20 seconds after opening the chamber door, a breakthrough of the gas-air mixture of the heat treatment chamber is observed through the supply shut-off jets at the edge of supply and exhaust hood. However, at a given flow rate of the removed air, the volume and temperature of the gas-air mixture leaving the edge of the hood are insignificant. Partial ejection of hot air coming out of the heat treatment chamber by the supply jets of the hood is noted without transferring them to the working area of the room.

30 seconds after opening the chamber door, the volume of hot air bursting through the edge of the hood increases. The maximum temperature of hot air at the place of the breakthrough reaches 35 °C. There is an insignificant removal of the volumes of the mixture of the supply air and the gas-air mixture of the chamber near the floor of the room due to the collision of the supply jets of the hood with it.

55 seconds after opening the chamber door, a part of the gas-air mixture that has broken through the supply and exhaust hood spreads in the upper part of the room. Due to the dilution of hot air in the room, the deviation of the gas temperature in the upper zone from the background values is insignificant. There is no active propagation of hot air breakthrough through the edge of the hood in the volume of the room. At the same time, an increase in the spread of the mixture of the supply air of the hood and hot air of the chamber in the lower part of the working area of the room is observed.

Removal of most of the volume of the gas-air mixture of the heat treatment chamber is completed 75 seconds after the chamber door is opened (Figure 7). The air temperature in the chamber volume exceeds 30 °C. No air breakthrough over the edge of the hood is observed; part of hot air that entered the room earlier is dispersed in the upper area of the room. The outlet of the mixture of the supply air of the hood and hot air of the chamber, carried by the supply jets of the supply and exhaust hood, has become widespread. The temperature in the working area in front of the chamber doorway does not exceed 25 °C.
Figure 5. Temperature fields in typical sections of the model after opening the door to the chamber (option 1 - an exhaust hood; supply and exhaust air flow rate is 5400 m³/h).
Option 2.2 - supply and exhaust hood; supply air flow rate in the room is 3480 m$^3$/h; supply air flow rate in the supply and exhaust hood through the holes for concentrated supply is 720 m$^3$/h; supply air flow rate in the supply and exhaust hood through nozzles is 300 m$^3$/h; exhaust air flow rate is 4500 m$^3$/h.

The calculation results are presented in Figures 8 and 9.

\begin{figure}[h]
\centering
\begin{tabular}{cc}
\includegraphics[width=0.4\textwidth]{velocity_fields.png} & \includegraphics[width=0.4\textwidth]{temperature_fields.png} \\
\end{tabular}
\caption{Fields of velocities and temperatures in typical sections of the model 75 seconds after opening the door to the chamber (option 1 - exhaust hood; supply and exhaust air flow rate is 5400 m$^3$/h).}
\end{figure}

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\begin{tabular}{cc}
\includegraphics[width=0.4\textwidth]{velocity_fields.png} & \includegraphics[width=0.4\textwidth]{temperature_fields.png} \\
\end{tabular}
\caption{Fields of velocities and temperatures in typical sections of the model 75 seconds after opening the door to the chamber (option 2.1 - supply and exhaust hood; supply air flow rate in the room is 3780 m$^3$/h; supply air flow rate in the supply and exhaust hood through openings for concentrated flow rate is 720 m$^3$/h; exhaust air flow rate is 4500 m$^3$/h).}
\end{figure}
Figure 8. Temperature fields in typical sections of the model (option 2.2 - supply and exhaust hood; supply air flow rate in the room is 3480 m$^3$/h; supply air flow rate in the supply and exhaust hood through openings for concentrated supply is 720 m$^3$/h; supply air flow rate in supply and exhaust hood through nozzles is 300 m$^3$/h; exhaust air flow is 4500 m$^3$/h).
Figure 9. Fields of velocities and temperatures in typical sections of the model 75 seconds after opening the door to the chamber (option 2.2 - supply and exhaust hood; supply air flow rate in the room is 3480 m$^3$/h; supply air flow rate in the supply and exhaust hood through openings for concentrated flow rate is 720 m$^3$/h; supply air flow rate in the supply and exhaust hood through nozzles is 300 m$^3$/h; exhaust air flow rate is 4500 m$^3$/h).

Figure 10. Fields of velocities and temperatures in typical sections of the model 110 seconds after opening the door to the chamber (option 2.2 - supply and exhaust hood; supply air flow rate in the room is 3480 m$^3$/h; supply air flow rate in the supply and exhaust hood through openings for concentrated flow rate is 720 m$^3$/h; supply air flow rate in the supply and exhaust hood through nozzles is 300 m$^3$/h; exhaust air flow rate is 4500 m$^3$/h).
10 seconds after opening the chamber door to the room, there is a significant deviation of the supply jets of the hood from the vertical axis towards the opening of the heat treatment chamber; at the floor, they merge with the supply jets of the inflow into the room and lay on the floor of the chamber.

20 seconds after opening the chamber door, hot air from the chamber enters the supply jets of the hood, however, due to their direction towards the doorway of the chamber, hot air does not escape into the working area. No breakthrough of the gas-air mixture of the chamber over the edge of the hood is observed.

30 seconds after opening the chamber door, the supply jets of the hood containing hot air from the chamber are laid on the floor, but due to their orientation towards the chamber doorway, the removal of the hot air mixture into the working area is insignificant. In contrast to the calculation of the supply and exhaust hood without air supply to the nozzles, a breakthrough of the gas-air mixture of the chamber is not observed.

55 seconds after opening the chamber door, the supply jets of the hood are aligned vertically with a slight displacement towards the chamber doorway, preventing hot air from escaping into the working area. An insignificant part of the mixture of hot air with the supply air, which got into the lower part of the working area, does not receive further distribution. Hot air does not break through the edge of the hood.

The removal of the gas-air mixture that was in the heat treatment chamber is completed 75 seconds after the chamber door is opened. The chamber is filled with a mixture of supply air and hot air with an average temperature of 30 °C. There is a slight removal of the air mixture by the supply jets beyond the edge of the supply and exhaust hood. This mixture of supply and hot air does not spread in the working area of the room.

Complete removal of the gas-air mixture from the space of the heat treatment chamber occurs at 110 seconds (Figure 10).

4. Conclusion
Air-jet covers provide more reliable trapping of harmful substances released in technological processes with significantly lower volumes of air removed. The use of a system of air jets acting as a screen that prevents the penetration of harmful substances from the “dirty” zone into the “clean” one allows reducing the consumption of supply and exhaust air.

The design of the supply and exhaust hood adopted for the study ensures that heat and gases coming out of the heat treatment chamber are captured at a 17% lower supply and exhaust air flow rate compared to the exhaust hood.

The supply and exhaust hood has a system of horizontal and vertical nozzles located on the lower and lateral (inner) sides of the hood, and air distributors that create concentrated jets for supplying air from top to bottom, which increases the efficiency of localizing the gas-air mixture breaking out from the heat treatment chamber.

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