Determining the effective drop size when modeling heat and moisture exchange in the spray chamber

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Abstract. A mathematical model of the motion of a water droplet in the air channel has been created taking into account heat and mass transfer (evaporation). A series of calculations are performed in the ANSYS CFX with various parameters including droplet diameter and temperature, moisture content and air temperature. The analysis and comparison of the simulation results are presented.

1. Introduction

Air conditioning and ventilation systems (HVAC) are intended to create and maintain the artificial climatic conditions. This industry is developing rapidly due to creation and development of new modern industries. Spray chambers are widely used in HVAC systems; however, due to a wide variety of initial parameters and various designs, they require detailed study [1].

The main parameters of HVAC systems are temperature and humidity. In order to facilitate proper conditions and increase working efficiency when designing new technological productions, unique buildings designed for a long stay of a large number of people, it is necessary to ensure air parameters to be in strictly defined range.

Depending on the parameters of the mixture entering into the installation and the working fluid, the concentration of water vapor in the incoming mixture can either decrease due to condensation of the vapor on the drops, or increase due to their evaporation. During phase transition processes, the temperature of the vapor – gas flow is changing, as well as the droplet size and velocity. The dynamics of processes in air-vapor-droplet media is characterized by the complex heat and mass transfer mechanisms and phase transformations.

To predict the composition of the emerging heterogeneous gas-vapor mixtures, to control the conditioning parameters and increase their efficiency, it is necessary to solve the coupled problem with taking into account many factors [2, 3]. Due to the lack of simple and cheap alternatives for air humidification, the study of heat and moisture exchange processes in irrigation chambers, the improvement of calculation methods and the design of these devices are urgent tasks.

Among recent published studies in the field of the propagation and interaction of liquid and gas droplets in air conditioning systems, papers [4–9] should be mentioned. To date, there is still no the general theory that describes the heat transfer of droplets in a spray chamber, and existing analytic formulas are valid only for conditions of adiabatic evaporation. The feature of this work is a based on
2. **Formulation of the problem**

In this paper, the movement of a single drop fed into the air channel is simulated to understand the process of heat-moisture exchange. At this stage, the interaction between drops is not taken into account. The calculation area (Fig. 1) is a cylinder filled with a resting vapor-air medium under the following parameters: pressure $P_\infty$, temperature $T_\infty$, density $\rho_\infty$, moisture concentration $W_\infty$. From the top cover, a water droplet of diameter $d_p$ is injected with a velocity $V_p$ at a temperature $T_p$. The gravity $g = 9.81 \text{ m/s}^2$ is directed along the axis of the cylinder. On the side walls, the symmetry conditions are specified ensuring impermeability and heat insulation. On the opposite cylinder surface which is the outlet section, a pressure of 1 atm is set.

![Figure 1. Geometry of the computational model: inlet section (1), output section (2), side wall (3), drop point (4), trajectory of a drop (5).](image)

3. **Mathematical model**

In this work, the problem is solved by computer simulation methods in the ANSYS CFX software [10]. For the study, a mixed Eulerian-Lagrangian formulation of the problem was chosen. The vapor-gas medium is described on the basis of the Euler approach in which the phases are considered as interpenetrating media. The mathematical model is based on the Reynolds-averaged Navier-Stokes equations taking into account the interfacial interaction closed with the $k-\varepsilon$ two-equation turbulence model with standard constants [11].

The movement of a drop of liquid is described based on the Lagrange approach:

$$\frac{d\mathbf{u}_p}{dt} = F_d (\mathbf{u}_g - \mathbf{u}_p) + \frac{g (\rho_p - \rho_g)}{\rho_p} + \mathbf{F},$$

where $F_d$ is the drag force; $\mathbf{u}_g$ is gas velocity; $\mathbf{u}_p$ is the drop velocity, $\rho_g$ is the gas density; and $\rho_p$ is the drop material density. Particle resistance force is calculated using the Schiller-Naumann model [12]:

$$F_d = \frac{C_D \text{Re}}{24},$$

where $C_D = \begin{cases} 24(1 + 0.15 \text{Re}^{0.687})/\text{Re} & \text{Re} \leq 1000 \\ 0.44 & \text{Re} > 1000 \end{cases}$.

Heat transfer to the environment is modeled using a Ranz-Marshall [13] approach:

$$Nu_p = 2 + 0.6 \cdot \text{Re}_p^{1/2} \text{Pr}^{1/3},$$
Interfacial mass transfer depends on whether the saturated vapor pressure of a drop is above or below the evaporation point, and is determined by the Antoine equation [14]:

$$\log P = A - \frac{B}{C + T},$$

where $A$, $B$, $C$ are the empirical constants, for $T < 100^\circ C$ they are equal to 8.07131, 1730.63 and 233.426, respectively [15]. The droplet is boiling if the vapor pressure $P_t$ is greater than the ambient gas pressure $P_\infty$. Mass transfer between the vapor-air medium and the water drop depends on the drop temperature:

$$\frac{dm_p}{dt} = \begin{cases} \frac{Q_C}{V} & \text{if } T_p > T_B \\ \pi \cdot d_p^2 \cdot \rho_p \cdot D \cdot Sh \cdot \frac{W_C}{W_G} \ln \left( \frac{1 - X_S}{1 - X_{vap}} \right) & \text{if } T_p < T_B \end{cases}$$

where $V$ is the latent heat of vaporization of the drops, $Q_C$ is the convective heat flux, $T_B$ means the boiling point, $d_p$ stands for the droplet diameter, $D$ is the diffusion coefficient, $Sh$ is the Sherwood number, $W_C$ and $W_G$ are the molecular weights of the vapour and the mixture in the continuous phase, $X_S$ is the equilibrium vapor mole fraction of the evaporating component at the droplet surface, $X_{vap}$ is the mole fraction of the evaporating component in the gas phase.

### 4. Calculation method

Numerical research is aimed at determining the influence of various parameters of the air mixture and the parameters of a drop on the process of heat-moisture exchange. Based on the mathematical model described above, a series of 3D calculations was performed in ANSYS CFX, in which the parameters of the drop ($d_p, T_p$) and the environment ($W_\infty, T_\infty$) were changed.

In the computational domain (Fig. 1), a structured computational hexa-mesh was constructed, a fragment of which is shown in Fig. 2. Three grids with the number of nodes of 115540 (coarse), 429416 (medium) and 807715 (fine) were investigated. The drop velocity was $V_p = 2 \text{ m/s}$; its diameter varied from 0.05 to 1 mm, and the temperature of a drop of $T_p$ lays in the range of 15 ÷ 45°C. At the initial moment, the parameters of the external vapor-air mixture are as follows: $V_\infty = 0 \text{ m/s}$; $T_\infty = 10^\circ C$, $17^\circ C$, $24^\circ C$ and $30^\circ C$; and the moisture concentration is $W_\infty = 1, 5$ and $10 \text{ g/kg}$. Totally, 180 variants are calculated with various combinations of the input parameters. The problem is solved as a steady-state.

The case of $T_\infty = 30^\circ C$, $T_p = 45^\circ C$, $W_\infty = 1 \text{ g/kg}$ is chosen for the grid independence study. The results are compared by the diameter, temperature, and speed of the drop. Since the results on the fine and medium grid differ by no more than 1.25%, the medium grid containing 429416 nodes is chosen for calculations. All further results are obtained on this grid.

![Figure 2. Fragment of the calculated medium grid.](image)
5. Results and discussion

As a result of the calculations, in all the cases studied, the fields of temperature, velocity, drop diameters, and concentration of water vapor are obtained. Evaporation rates of droplets of various diameters are compared for various external conditions. From the efficiency point of view, the best humidification process in the spray chamber is that in which the water drop evaporates completely during its passage through the chamber. The drop with the smallest diameter evaporates faster but the equipment for the preparation of water and its spray is more expensive. Below there are the results of the most intense humidification processes with high $T_p$ and $T_\infty$ and low moisture content $W_\infty$.

Figure 3a presents the relative size of droplets, $y$, of various initial diameters depending on the distance from the injection point $x$ under the following conditions: $T_\infty=30^\circ\text{C}$, $W_\infty=1\ \text{g/kg}$, $T_p=45^\circ\text{C}$. It can be seen that the droplets of $d=0.1$ and $0.05\ \text{mm}$ are completely evaporated during the fall, which is the optimal variant under the given conditions.

Figure 3b shows $y$ variation under various $T_\infty$ for droplets with diameters $d=0.1$ and $0.05\ \text{mm}$ that are find to be optimal in Fig. 3a under the conditions $W_\infty=1\ \text{g/kg}$, $T_p=45^\circ\text{C}$. If $T_\infty<24^\circ\text{C}$, then drops of $d=0.1\ \text{mm}$ do not have time to evaporate. In reality, incomplete evaporation will lead to additional consumption of working fluid.

In Fig. 4, the water vapor concentration fields are shown in the central section computed under the conditions $T_\infty=30^\circ\text{C}$, $W_\infty=1\ \text{g/kg}$, $T_p=45^\circ\text{C}$ and $d_p=1$ (A), 0.5 (B), 0.2 (C), 0.1 (D), and 0.05 mm (E). Figure shows that the concentration is maximum in the case A, this is due to the larger surface of the droplet and the larger ambient and droplet temperature difference.

Figure 5 presents droplet temperature $T_p$ for droplets of various diameters: $d_p=1$ (A), 0.5 (B), 0.2 (C), 0.1 (D) and 0.05 mm (E) at $W_\infty=1\ \text{g/kg}$, $T_\infty=30^\circ\text{C}$. In the case of big droplets (A and B cases), the humidification process is the most intensive due to the high droplet temperature, but the big size of the droplets does not allow them to evaporate completely during the path. In the cases of smaller droplets (D and E), the droplets are evaporated completely and their temperature reaches minimum at the very beginning of the trajectory.
Figure 4. The concentration of water vapor at $T_\infty = 30^\circ$C, $W_\infty = 1$ g/kg, $T_p = 45^\circ$C and $d_p = 1$ (A), 0.5 (B), 0.2 (C), 0.1 (D) and 0.05 mm (E).

Figure 5. The change in $T_p$ of different diameters at $W_\infty = 1$ g/kg, $T_\infty = 30^\circ$C and $d_p = 1$ (A), 0.5 (B), 0.2 (C), 0.1 (D) and 0.05 mm (E).
Conclusion
In the paper, a mathematical model of the isolated water droplet movement in the air channel is created taking into account heat and mass transfer (evaporation). As a result of the simulation, the parameters of evaporation of single water droplet under various conditions are found. A comparison of the evaporation process for the droplets of various diameters and temperatures is made and the optimal droplet parameters are found which can be used for HVAC design. Based on the analysis of the simulation results, it is shown that the use of droplets with a diameter larger than 0.05 mm in the spray chambers is impractical due to their incomplete evaporation even for the case of a single drop. In the future, the constructed computational model can be used to simulate processes with taking into account the droplets interaction.

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