Numerical modelling of a two-channel heat and mass exchanger

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Abstract. This work is devoted to the study of heat and mass transfer apparatus of indirect-evaporative type. This device consists of two channels, in one of which the processes of heat and mass transfer occur. This scheme is known in the literature as the By-pass scheme. Numerical studies of laminar flow and heat and mass transfer are carried out with variations in the input parameters (Reynolds number Re=100, temperature $T_0 = 26 \pm 32^\circ C$ and relative humidity $\varphi_0 = 40 \pm 70\%$). The resulting cooling effect in such a heat and mass transfer apparatus can be quite high and comparable with traditional air conditioning schemes, including steam-compression refrigeration machines.

1. Introduction
Heat exchangers with evaporative cooling, implemented in their channels, are one of the simple and quite effective ways to reduce the temperature of air or liquid flows. If the cooled useful air in the heat exchanger is not in contact with the evaporating liquid, such heat and mass transfer devices are attributed to the indirect-evaporative type. In devices of direct and indirect evaporative type, the limit value of cooling is the temperature of the wet thermometer.

When the pre-cooled air is fed to the inlet of the evaporative channel by a heat sink from the dry channel, as shown in Fig. 1, then in this kind of feedback system the theoretical limit of cooling is the "dew point". Systems operating on a similar principle are called the Maisotsenko cycle (M-cycle) [1] and they are widely used in air conditioning systems and cooling components of electronic equipment.

Currently, the thermal characteristics of devices using the M-cycle are actively studied experimentally and theoretically [2-7]. The investigation of regularities of heat and mass transfer processes in the channels of heat and mass transfer devices is an important step in the study of more complex indirect evaporative cells.

This work is devoted to the numerical study of the flow and heat and mass transfer in the heat and mass transfer apparatus, which is a system of two channels, in one of which the wall is wetted with a thin film of water. Such a device is the most simple in comparison with multi-channel systems. However, it is quite easy to analyze the limitations of the M-cycle in this apparatus and transfer them further to the multi-channel heat exchangers. At the same time, the simplicity of the design of such devices is of independent practical interest that may condition their further practical implementation. Particular attention is paid to the influence of the input parameters (input temperature and relative humidity, as well as the Reynolds number) on the air parameters at the outlet of the device.
2. Modelling and analysis

The scheme of the problem is shown in Fig. 1. The heat-and-mass transfer apparatus consists of two plane-parallel channels of the same height of 5 mm. Part of the flow from the dry channel with a low temperature is directed to the channel with wet walls. Thereby, it is possible to obtain a temperature at its outlet close to the dew point temperature, determined by the air parameters at the inlet \( (\text{Re}, T_0, \phi_0) \). The flow mode is laminar and stationary, and the flow is stabilized. From outside, the device plates are insulated, and inside, the walls of the wet channel are wetted with a film of water. Radiant heat exchange, viscous dissipation and the effects of Dufour and Soret were neglected.

The system of equations, which allows determining the main parameters in the heat and mass transfer apparatus, is as follows

- The equation of the heat balance of the final volume under consideration:

\[
G_{\text{dry}} c_p \left( T_{\text{dry} \rightarrow \text{out}}^{\text{in}} - T_{\text{dry} \rightarrow \text{out}}^{\text{out}} \right) = \alpha \left( T_{\text{dry} \rightarrow \text{out}}^{\text{dry}} - T_{\text{dry} \rightarrow \text{out}}^{\text{in}} \right) dx ,
\]

where \( \alpha \) is the coefficient of heat transfer and \( G \) is the mass flow rate of air. Equation (1) means that the change in the air flow enthalpy in the dry channel is equal to the total heat transfer between the air flow and the water film.

- The law of conservation of energy for the air flow in a wet channel gives:

\[
G_{\text{wet}} \left( h_{\text{wet} \rightarrow \text{out}}^{\text{in}} - h_{\text{wet} \rightarrow \text{out}}^{\text{in}} \right) = \beta \left( h_{\text{wet} \rightarrow \text{out}}^{\text{wet}} - h_{\text{wet} \rightarrow \text{out}}^{\text{in}} \right) dx ,
\]

where \( \beta \) is the mass transfer coefficient. The left part in (2) determines the change in the air flow enthalpy in the wet channel, and the right part shows the total energy transfer by convective heat and mass transfer between the air flow and the water film.

- The law of conservation of energy in a differential element can be written as

\[
G_{\text{dry}} c_p \left( T_{\text{dry} \rightarrow \text{out}}^{\text{in}} - T_{\text{dry} \rightarrow \text{out}}^{\text{out}} \right) = G_{\text{wet}} \left( h_{\text{wet} \rightarrow \text{out}}^{\text{in}} - h_{\text{wet} \rightarrow \text{out}}^{\text{in}} \right) dx .
\]

Expression (3) means that the change in the air flow enthalpy in the dry channel is equal to that in the wet channel.

- Finally, the law of conservation of energy in the wet channel:

\[
G_{\text{wet}} \left( d_{\text{wet} \rightarrow \text{out}}^{\text{in}} - d_{\text{wet} \rightarrow \text{out}}^{\text{in}} \right) = \beta \left( d_{\text{wet} \rightarrow \text{in}}^{\text{in}} - d_{\text{wet} \rightarrow \text{in}} \right) dx ,
\]

where \( d \) is the air humidity in the wet channel. The left part of expression (4) is the change in the air flow humidity in the wet channel, and the right part characterizes convective mass transfer between the air flow and the water film. Heat and mass transfer coefficients were calculated according to [7].

The ratio of flow rates over the dry and wet channels is estimated by expression:

![Figure 1. The computational scheme of heat and mass transfer apparatus.](image-url)
The mathematical model of the heat and mass transfer apparatus is based on the numerical method of calculating the main parameters of air flows, such as temperature, relative humidity, and moisture content (humidity). The discretization of the system of differential equations was carried out on a uniform grid with the optimal number of nodes of 500 cells. The reliability of the developed program was evaluated by comparing the obtained data with the results of numerical [2] and experimental [5] studies. The results of such comparisons for the values of the gas flow temperature at the outlet with variations in the inlet air temperature and humidity are shown in Fig. 2. It is possible to note a good agreement of the results of this work and the numerical and experimental data of other authors.

\[ m = \frac{G_{dy}}{G_{wet}}, \]

The change in thermogasdynamic parameters of air over the HEA length for dry and wet channels at the by-pass ratio \( m = 0.3 \) is shown in Fig. 3. It can be seen that the average mass temperature of the air in the dry channel due to heat exchange with the wet channel, where water evaporation occurs, decreases rapidly along the length. In addition, there is a minimum in the temperature distribution along the length of the wet channel. It is due to the removal of heat to the phase transition, and on the other hand, due to the supply of heat from the dry channel. In the dry channel, the relative humidity increases monotonically due to the gas temperature decrease with its propagation. It should be kept in mind that the absolute moisture content remains unchanged. The temperature decrease towards the dry channel output is the main positive factor of the considered scheme of the heat and mass transfer apparatus of the indirect-evaporative type. Indeed, according to Fig. 3, air with a temperature of about half of its value in the ambient space is supplied to the evaporation channel inlet. In the wet channel, the relative humidity reaches 100%. The main drawback of the considered scheme of heat and mass transfer apparatus is a decrease in the mass flow of dry air at the device outlet (\( G_{dy} \)). In addition, the cooling efficiency is significantly reduced with increasing ambient humidity.
From Fig. 3 it may be also inferred that the air temperature in the dry channel has reached the temperature of the wet thermometer \( T_{w.b.} \) and is monotonically approaching the dew point temperature \( T_{d.p.} \), which is the theoretical limit of cooling in this unit.

Conclusion

The numerical analysis of characteristics of the two-channel heat and mass transfer apparatus of indirect evaporative type has been carried out. The resulting cooling effect in devices of this type can be quite high and comparable with traditional air conditioning schemes, including vapor compression refrigeration machines. The heat and mass transfer apparatus with the considered coolant flow scheme has high efficiency, low specific cost, low operating costs, and design simplicity. It has been found out that air coolers of indirect evaporative type have a number of positive characteristics and can be used not only as coolers, but also as humidifiers of air flows. The obtained data can be used for the optimization analysis of air cooling at variation of Reynolds number, air humidity, channel length and geometric dimensions of the channels. Presumably, similar tendencies will be observed at other temperatures and humidity of air at the device input, however this conclusion requires additional calculations.

Acknowledgments

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