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Research Paper

Influence of condensation on the efficiency of regenerative heat exchanger for ventilation

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HIGHLIGHTS

- The model of the heat exchanger with periodic change in the airflow direction was developed.
- The model takes into account the phase transitions on walls of the channel and in a flow.
- Sensible and latent efficiency of the regenerative heat exchanger were determined.
- Parameters of an ice formation in the heat exchanger were found.

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ABSTRACT

The paper presents a physical and mathematical model for calculating the air-to-air heat exchanger with periodically changing direction of the air flow. It accounts for vaporization and condensation on the channel walls of the heat exchange matrix with regular structure as well as possible formation of water fog directly in the air flow. The model can be used to analyze the influence of operating parameters, the geometric dimensions of the channels and properties of the used materials on the work efficiency of the heat exchanger. The results of calculations of the influence of indoor air humidity on heat and moisture transfer processes in the regenerative heat exchanger are provided. Sensible and latent efficiency of the regenerative heat exchanger as well as their dependence on relative humidity of indoor air are determined. The relationship between the outdoor air temperature and relative humidity of indoor air, at which ice formation begins in the channels of the heat exchange matrix, is found.

1. Introduction

The International Energy Agency cites that in the period between 1991 and 2012, the population growth was 30%, while over the same period, the total primary energy supply increased 3 times faster. In European Union in 2010, buildings accounted for 40% of total primary energy [1]. In the industrial countries up to 50% of carbon dioxide emissions come from the building sector [2,3]. The worldwide experience in exploitation of high-rise and low-rise residential buildings shows that the highest energy costs are associated with heating, ventilation and air conditioning, reaching up to 50% in the overall balance of residential buildings [4].

In recent years, increasing requirements for thermal insulation of claddings and for reduction of their air permeability has led to an increase in the share of heat losses associated with ventilation. According to [5], more than 50% of the total energy loss in buildings with high level of thermal insulation may be due to ventilation losses. Therefore, of particular relevance at present are energy-efficient ventilation systems with recovery of the ventilation air heat and cold.

A number of European countries, especially the Nordic countries, are introducing regulatory requirements on the use of energy saving ventilation systems in the newly constructed buildings. For example, the 2010 Danish building regulations require heat recovery with a temperature efficiency of 70% for ventilation of entire buildings and 80% for single dwellings. The 2020 regulations will increase these requirements to 75% and 85%, respectively [6].

The widest applied in the ventilation systems with heat recovery (VHR) are recuperates [7–10]. In them, the air flows are separated and do not mix, which ensures high quality of the incoming air. The used polymeric materials have significantly reduced the weight of heat exchangers [11,12]. Recently, much attention has been paid to the study of membrane heat and moisture transfer devices [13–15]. There the partition separating gas

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Nomenclature

C	specific isobaric heat capacity, J/(kg·°C)
f	fog content in air, kg/kg
h	specific enthalpy, J/kg
j	mass flux, kg/(m^2·s)
L	channel length, m
Le	Lewis number
Nu	Nusselt number
q	heat flux, J/m^2
P	pressure of air, Pa
r	heat of vaporization, J/kg
Re	Reynolds number
S	area of the channel cross-section, m^2
S_m	area of the channel wall cross-section, m^2
t	temperature, °C
t_a, t_m	air and matrix temperature, °C
u	airflow velocity, m/s
x	longitudinal coordinate, m

Greek symbols

α	heat transfer coefficient, W/(m^2·°C)
β	mass transfer coefficient, kg/(m^2·s)
ε	efficiency of heat exchanger
η	moisture content of channel, kg/kg
λ	coefficient of heat conductivity, W/(m·°C)
Π	perimeter of the air passage cross-section, m
ρ	density, kg/m^3
τ	time, s
φ	relative humidity of air
χ	coefficient of thermal diffusivity, m^2/s
ω	humidity ratio of moist air, kg/kg
ω_S	saturated humidity ratio of moist air, kg/kg

Subscripts

a	air
f	fog
m	matrix
L	latent
S	sensible, saturated

Superscripts

a	air
m	matrix
v	vapor
w	water

flows is a membrane permeable to water vapor, through which the gas flows exchange both heat and moisture.

A particular group of VHR-devices is air-to-air heat exchangers with intermediate heat carriers. The main advantage of such devices is the spatial separation of the ventilation air input and output, which simplifies the use of mechanical ventilation systems. Lately, such devices have been widely applying membrane technologies [16,17].

High efficiency of ventilation air cold and heat recovery is specific for periodic heat exchangers. According to the classification proposed by Kays and London [18], periodic heat exchangers are divided into rotating and switching ones. Rotating machines are regenerative air-to-air heat exchangers with rotating actuating media, the so-called recovery wheels [19–21]. The rotating body in them is either a porous material or a matrix with regular mini-channels, which is blown off by air flows of different temperatures. The effective designs of rotating heat exchangers from nonmetallic materials were proposed and investigated in [22]. The use of sorbent materials [23] or special sorbent coatings on the surfaces of rotating regenerative heat exchangers [24–26] allows not only heat transfer but also moisture exchange between air flows in such devices.

Another type of periodic regenerators is air-to-air heat exchangers with periodic change of air flow direction. There is less research on such machines than on the rotating ones. There are publications, containing research results on the regenerators of this type with heat-exchange elements in the form of fillings [27–30], or matrices with regular mini-channels [31,32]. These devices are quite compact; their work requires little electric power; and they can be used to organize energy saving ventilation in separate apartments or even rooms in residential buildings.

When recuperative or regenerative air-to-air heat exchangers operate at low outdoor temperatures there are problems associated with moisture condensation. At temperatures below 0 °C ice formation may occur on heat exchange surfaces [33–35]. The freezing-up of the heat exchanger leads to partial or complete blockage of the air channels, increase in hydraulic resistance, drop of the air flow and overall reduction in their efficiency. Various approaches to prevent condensation and ice formation are examined to combat these phenomena [36–39]. However, all of them either lead to additional energy costs or reduce the heat exchanger efficiency.

In heat exchangers, where the flows exchange not only heat but moisture, condensation and formation of ice are observed at lower temperatures than in conventional heat exchangers [35]. So, in [40–42], it was noted that the frost forms approximately 5–10 °C lower in a desiccant wheel than in the conventional one. A similar effect of lowering the ice formation temperature was noted in the membrane energy exchanger [43]. It should be noted that, despite considerable attention to the issues of condensation and ice formation in regenerative and recuperative air-to-air heat exchangers, these problems remain acute and little studied for the membrane [15] and periodic heat exchangers.

Theoretical models for calculating periodic heat exchangers of rotating types considering processes of condensation and evaporation are given in [44]. The physical and mathematical model for calculating the air-to-air heat exchanger with periodic change of air flow direction and its verification on the experimental data are described in our previous work [32]. The present work further develops the mentioned computational model, taking into account possible processes of condensation and evaporation both on the channel walls and directly in the form of water fog in air flows. As a result of calculations it is shown that the phase transitions at certain temperatures and humidity of the air flows can have a considerable impact on sensible and latent efficiency of such a device. Using the proposed model it has become possible to determine temperature and humidity boundary of the operation modes of the heat exchanger, in which ice formation starts in the channels of the heat exchange matrix.

2. Problem statement

Fig. 1 schematically shows the air-to-air regenerative heat exchanger with periodically changing direction of the air flow. The exchanger comprises of a heat exchange matrix through which