

The computer simulation of hoarfrost's clearing process in the air recuperation system

F V Savrasov, S V Prokhorov, A A Shilin

Tomsk Polytechnic University, 30, Lenina ave., Tomsk, 634050, Russia

E-mail: savrasov@tpu.ru

Abstract. This paper observes an air recuperation system, which proposes the variable frequency drive control mode, ensuring the maintenance of the outgoing air temperature to the dew point to reduce the hoarfrost layer. A mathematical model of the dynamic processes of hoarfrost layer's appearance, allowing the investigation of setting methods of an enclosed temperature control system of inlet air and determination of the structure of this system, is proposed. The algorithm of switching between recuperation modes within the framework of the functioning system is investigated.

1. Introduction

Many modern methods of heat savings in ventilation systems include recuperative facilities that have taken opportunities of using of the warmth of the heated air from the room to heat the incoming fresh air. The efficiency of that system is very high, especially in the regions where the supply air temperature can estimate the value below $-25\text{ }^{\circ}\text{C}$. Constructive implementation of energy recuperators can be different [1, 2, 3, 4]. However, the general principle of operations can be represented in Figure 1, where the recuperator is a device that produces heat exchange between the incoming air and the outgoing inside air. As a result, fresh air, entering the ventilation system, is heated up, and the air, coming out from the heat exchanger to external environment, is cooled down. It ensures minimization of heat losses in ventilation installations.

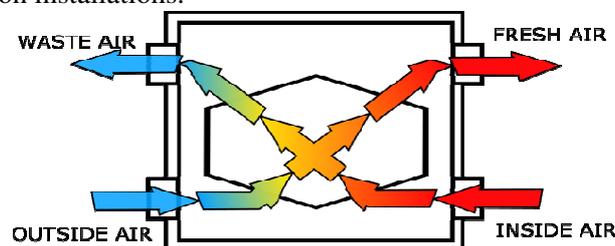


Figure 1. The principle of heat exchanger's functioning.

There are special facilities, where even partial consistency mixing of the incoming and outgoing air, providing by drum recuperators [2], is unacceptable. For such systems, recuperators with intermediate coolant are used, which provide a complete physical isolation of both air flows, and the heat process is proceeded by an intermediate coolant circulating between two isolated air-heat exchangers. The circulation pump with an induction motor executes a motion of the intermediate

coolant. In regions, where (at winter time) the temperature drops below $-25\text{ }^{\circ}\text{C}$, the problem of hoarfrost occurs.

A hoarfrost formation phenomenon relates to the fact that moist air at the outlet of the recuperative installation condenses and then freezes in contact with the cooled surface of the ventilation heat exchanger. The problem of defrosting this layer in the recuperative ventilation system is very actual, as the excrescences of hoarfrost can cause low air circulation, large energy load of fan motors, deterioration of heat transfer within the system, and even shutting down the system in case of formation of a thick layer of hoarfrost. This problem is relevant for countries such as Russia, Canada, Denmark [5, 6] and others, which are actively developing the features to solve this problem in energy-efficient ventilation systems.

One of the main methods of getting out of hoarfrost excrescences has been considered in [5], it suggests the introduction of resource-efficient technologies in residential buildings in Canada. A defrosting process is performed using stoves that have been implemented into the ventilation system. If the formation of the value of the hoarfrost layer is above the permissible, the sensors report the actuator on the necessity to switch on the heaters. The latter, in its turn, melts the hoarfrost by a dedicated heat.

This method has the disadvantages associated with the necessity to change the structure of the air shaft and the uneconomic use of heating elements.

Another method is based on the recovery waste-heat exchanger with cross-flowing channels, which gets rid of the hoarfrost excrescences by rotation around its axis by 180° . The value of hoarfrost formation therein is determined either by temperature sensors located at the far corner of the facility or via the differential pressure sensor.

The disadvantage of this method is that for rotation of the heat exchanger around its axis, an extra gear that implements this movement is required. Also, using this method of the rotating heat exchanger at the moment when hoarfrost excrescence is above the critical value, the performance of heat exchanger decreases, that leads to the leak of thermal energy, used in the defrost process.

In view of the above mentioned, the results of the synthesis of the structure and a mathematical model, that adequately describes the dynamic processes of hoarfrost formation and defrosting in the recuperative system with an intermediate heat transfer, are performed in this paper. These results allow exploring ways to solve the problem of using modern technical possibilities.

2. Modeling system

The solution has been proposed, the main idea of which is to implement the mode of the recuperative system working in the dew point. This mode reduces the hoarfrost layer, herewith the decline of the recuperative facility's efficiency is significantly less than during heating the channel of outgoing air. The temperature mode in the dew point will maintain the output temperature sufficient to the defrosting. Authors propose to use a variable frequency drive in the circulation of the coolant circuit, which will provide two modes:

1. the maximum effective heat transfer, wherein the layer of hoarfrost is increasing;
2. the mode of maintaining the dew point, wherein the maximum possible heat transfer is ensured and the layer of hoarfrost is reduced.

The advantage of this method is that its implementation is sufficient to control the frequency of the asynchronous motor of the pump. The topicality of such decision becomes pronounced due to a significant reduction in the cost of the induction motor's inverter device. It makes this solution very affordable. The programmable logic controller is assumed as a main control device. The amount of the formed hoarfrost is determined by an analogue or digital differential pressure sensor.

The functional diagram of the proposed recuperative system is shown in Figure 2. This figure shows the heat exchangers at inflow 1 and outflow 2, pump 3, the frequency converter (FC) and the programmable logic controller (PLC), heated 4 and cooled heat-transfer material 5, temperature sensor 6, differential pressure sensor 7, which compares the pressure before and after the coolant in the exhaust part of the heat recovery system.

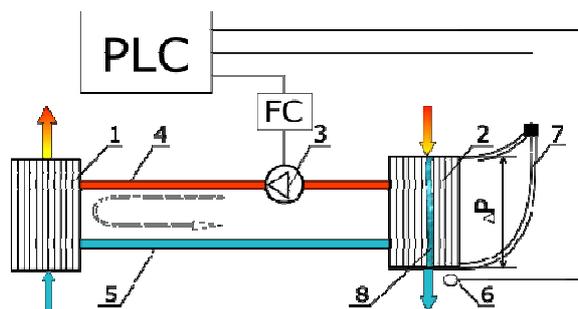


Figure 2. The functional scheme of the defrosting system.

The functioning of the recuperative system is heat recycling of cooled air which is transferred to the heater of the fresh outside air from working pump 4. When the electric engines of exhaust and supply fans are working, pump 4 puts in the pipeline of heat exchanger 1 (extracting the heat) the antifreeze (as a heat-transfer material) with negative temperature. Antifreeze, passing through the pipes, is heating to a certain positive temperature due to the heat from the outgoing air flow. At the same time, the condensate begins to increase on the plates of outflow heat exchanger 2. This condensate at low temperatures freezes and forms a layer of hoarfrost. When the critical thickness of the layer is reached, the value of the differential pressure sensor increases to a predetermined value at which the system should be set to maintain the mode of the dew point.

A programmable controller in the enclosed system of temperature control of outgoing air generates a special signal to the frequency converter. As a result, with a decrease of the engine rotational speed of the circulating pump, the efficiency of the recuperative facility reduces. Herewith, a dew point temperature is maintained in the zone of hoarfrost excrescences of heat exchanger 2 (for the defrosting process). Thus, after clearing the ways for air flow transmitting, the value of differential pressure will decrease to a predetermined value corresponding to the absence of hoarfrost. After the refining of the heat exchanger from hoarfrost, the controller generates a special signal to the frequency converter, corresponding to the transition to the maximum circulation speed. In this mode, the heat exchanger's efficiency is maximized.

3. Computer simulation

Due to the fact that processes of heating and increasing of the hoarfrost layer are inertial and in many ways similar to known models of heat exchange systems, differential equations from [7] have been adopted. Also, for the synthesis of an enclosed system with PID control, it is possible to use linearization techniques of the controlled object [8] represented by the block diagram of the dynamic elements. Main principles of sensor polling were adopted from [9]. As a result, the model was created in the XCOS SciLab software environment (it is presented in Figure 3).

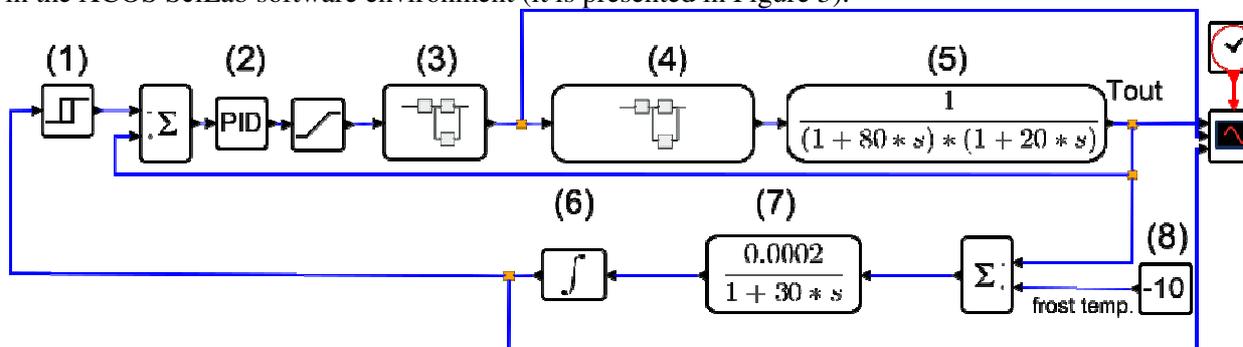


Figure 3. The model of the system in SciLab.

As an executive element of the system, a circulation pump is used, which, depending on control voltage U_{fc} on the frequency inverter, changes the speed rate of the coolant proportionally. A dynamic

model, representing the dependence of the coolant velocity on the voltage, is obtained by the mathematical model presented in [10] built for the induction motor with a squirrel-cage rotor and a controlled frequency converter. Due to the fact that the transient of hoarfrost is increasing and heating proceeds much slower than the transients of the engine, the main goal of this investigation is only a model of transition when the control voltage is changing. It is proposed to use a mathematical model of the oscillating level in the form of the transfer function:

$$F_t = [(1 + T_{fc}D)(1 + T_{m1}D + T_{m2}D^2)]^{-1}$$

where $T_{fc}=0.2$ s — the inertial moment of the frequency converter, $T_{m1}=0.15$ s, $T_{m2}=0.03$ s — dynamic parameters of the oscillating transition of the induction motor's model, D —Laplace operator. Presented parameters provide similar values of oscillation and overshoot to the full model in [10]. The transfer function is implemented in superblock 4.

The frequency converter is simplified to an aperiodic element of the first order. Transient of speed frequency's changing of the induction motor for the closed-loop system is represented by a second-order element, according to a mathematical model from [10]. When transients of the full model and a replacing element have been compared, it was concluded that the oscillation and overshoot were similar.

The static relationship between control signal U_{fc} and temperature of the air, outgoing to the external environment, T_{oa} , is represented as function

$$T_{oa} = 0.1k_{ef}(T_{out} - T_{rm})U_{fc} + T_{rm},$$

where T_{rm} — room temperature, T_{out} — external air temperature, k_{ef} — recuperation efficiency's factor. This static relation is realized in superblock 3. The function shows a voltage value that will correspond to the inlet temperature, taking into account the efficiency of the heat exchanger.

The dynamic part of the element that characterizes the changing of T_{out} , is represented by two serially connected aperiodic elements of the first order 5, with time constants $T_{i1}=80$ s, $T_{i2}=20$ s. These constants are selected from the description of the acceleration curves obtained from the experimental results from the existing installation.

The mode of appearance or melting of hoarfrost is determined by parameter T_{dp} — dew point temperature, which is represented by the physical meaning of the boundary temperature of the air, outgoing to the external environment. If the temperature is higher than this value, there is a mode of hoarfrost's melting, otherwise— the mode of the hoarfrost's growth. The process of transition in the freezing or thawing mode is also an aperiodic element of the first order with time constant $T_{cld}=30$ s and transfer coefficient $k_p=0.0002$, unit 7. The process of the growth and melting of hoarfrost in the heat exchange channel is represented by integrating element 6. The growth rate is determined by transfer coefficient k_p .

Also, the standard control elements are included in the model: hysteresis element 1 providing the switching of system modes in a predetermined range, the PI-controller 2 and the limiter — a unit that limits the maximum possible value of driving voltage.

In the feedback loop control system, the setpoint values of T_{oa} equals -15 °C (the value of differential pressure $\Delta P < 0.1$ kPa) in the active heat exchange mode and equals 1 °C ($\Delta P > 0.8$ kPa) in the mode of the maintaining the dew point. Switching between the modes is provided by the hysteresis element.

Transient processes in the automated system of protection against the hoarfrost are presented below (Figure 4).

The behavior of main variables of the observed system state, presented on transient charts, corresponds to the transition process, obtained from the real object, so this model adequately represents the dynamic processes of hoarfrost occurrence and thaw.

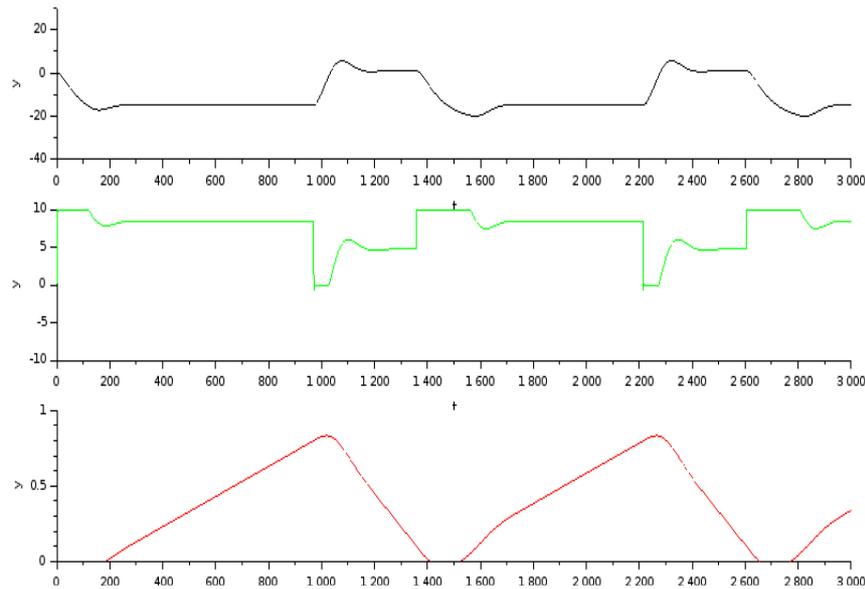


Figure 4. Transient performance of the outgoing air's temperature, the induction motor with the frequency converter unit, and the circuit, preserved from freezing

4. Conclusion

In this paper the solution to the problem of hoarfrost appearance in the recuperative ventilation systems was proposed. The basic idea is to use the method, maintaining temperature of dew point in the heat exchanger outlet, in case of hoarfrost occurrence. This method has the following advantages over the solutions observed in methods described above:

- it is easy to implement;
- the prevalence and inexpensive cost of variable frequency drives;
- efficiency of recuperative facility (since there is only a temporary loss of efficiency when facility is operating in a defrost mode).

A mathematical model describing the processes, occurring in the facility, can be useful in case of creation of mathematical models for ventilation control systems and in the formation of software for programmable logic controllers. This model can be recommended as an approach to the modeling of existing systems.

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