Heat and mass transfer analysis of cross-flow heat exchanger for energy recovery from exhaust air

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ABSTRACT
Problems of heat and mass transfer optimization in the plate cross-flow heat exchangers, used in air conditioning systems for energy recovery from exhaust air, are discussed. The main peculiarity of the investigated unit is the possibility of realization of heat transfer within exhaust air canals in the 'dry' heat exchange conditions or in the conditions of coupled heat and mass transfer with occurrence of vapour condensation on the whole or on a part of the heat exchange surface of the matrix in the form of dew or frost. The paper contains results of cross-flow heat exchanger investigations, obtained on the basis of complex research by using modern methods of optimization. The influence of the main dimensionless factors, affecting the efficiency of the cross-flow heat exchangers, has been investigated. The received results offer scope for estimation of optimal operating condition range variations for heat exchangers, used in air conditioning systems for energy recovery.

INDEX TERMS
HVAC; Energy; Improved IAQ practices and technologies; Heat transfer

INTRODUCTION
Plate heat exchangers are used in air conditioning systems for energy recovery from exhaust air. The distinctive peculiarity of the investigated unit is the construction of PHE packing, made of capillary porous plates, one side of which covered by moisture-resistant coating (Anisimov, 1996). Plates are arranged in such a way that outside airflow passages are formed by moisture-resistant surfaces and exhaust airflow passages by capillary porous surfaces. Such arrangement of plates makes possible to eliminate evaporation in outside air passages and, consequently, to raise the degree of energy recovery from exhaust air at the expense of efficient phase change heat utilization. Besides, there are no *choking* operating conditions when using this kind of matrix. However, the substantiation of potential efficiency of heat and mass transfer processes and optimum operating conditions of this recuperator requires detailed theoretical analysis. The present report is concerned with problem of optimization of coupled heat and mass transfer in cross-flow plastic plate heat exchanger (PPHE).

METHODS
The processes in PPHE are characterized by the presence of three different active coupled heat and mass transfer zones (see Figure 1). The analysis of heat and mass transfer process in these zones gives the possibility to raise thermodynamic perfection of investigated recuperator at the expense of efficient phase change heat recovery.

The complexity and labour-consuming character of comprehensive research of coupled heat and mass transfer in cross-flow heat exchanger matrix (Figure 2), as well as a large number of regulated parameters and wide range variation of their initial values, require using optimization methods of searching for heat exchanger rational operating conditions. One of

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the main conditions of successful realization of these methods is the selection of characteristic effectiveness indexes, such as:

- temperature effectiveness of supply air heating $\theta = \left(\bar{t}_{\text{co}} - t_{\text{ce}}\right) / \left(t_{\text{he}} - t_{\text{ce}}\right)$;
- enthalpy effectiveness of supply air heating

$$E_i \Big|_{\overline{W}_{\text{c}}/\overline{W}_{\text{h}} \,\le\, \left(i_{\text{he}} - i_{\text{ce,sat}}\right)/c_p\cdot\left(t_{\text{he}} - t_{\text{ce}}\right)} = \left(\bar{t}_{\text{co}} - t_{\text{ce}}\right) \Big/ \left(t_{\text{he}} - t_{\text{ce}}\right),$$

$$E_i \Big|_{\overline{W}_{\text{c}}/\overline{W}_{\text{h}} \,>\, \left(i_{\text{he}} - i_{\text{ce,sat}}\right)/c_p\cdot\left(t_{\text{he}} - t_{\text{ce}}\right)} = \left(i_{\text{he}} - \bar{i}_{\text{ho}}\right) \Big/ \left(i_{\text{hp}} - i_{\text{ce,sat}}\right);$$

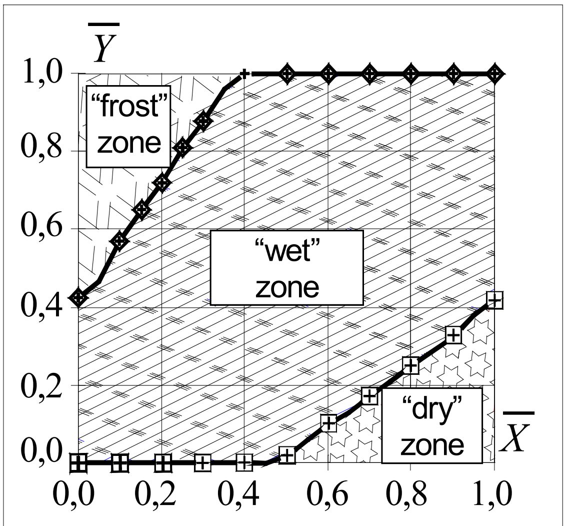

Figure 1 Active coupled heat and mass transfer zones in cross-flow recuperator channels.

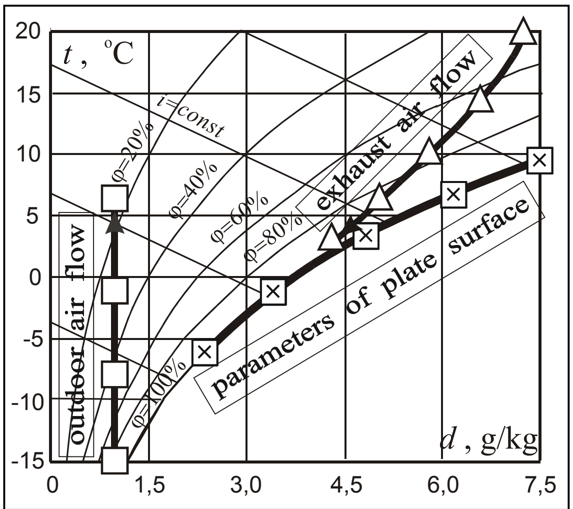

Figure 2 *I–d*-chart, showing the air state paths of outdoor and exhaust air streams in recuperator matrix.

- heat transfer rate from exhaust airflow to outside airflow per unit of heat exchanger matrix volume $\overline{Q}$, kW/m^3;
- heat transfer rate from exhaust airflow to outside airflow per unit of input power Q/N;
- relative area of heat exchanger matrix surface of possible frost deposition $\overline{F}_{\text{ice}} = F_{\text{ice}} / F_{\Sigma}$.

Independent input parameters and operating conditions, establishing in the unique fashion the values of exchanged air streams thermodynamic parameters on the exit of appropriate channels of heat exchanger package, can be proposed as follows:

- intake outdoor airflow temperature t_{ce}, °C;
- intake exhaust airflow temperature t_{he}, °C;
- intake exhaust airflow relative humidity φ_{he}, %;
- velocity of exhaust air stream in matrix passages w_{h}, m/s;
- outdoor air stream to exhaust air stream specific heat capacity rate ratio $\overline{W}_{\text{c}}/\overline{W}_{\text{h}}$.

Ranges of intake exhaust airflow temperature and relative humidity values variation were chosen on the basis of air quality demand rates t_{he} = (14–22)°C, φ_{he} = (15–75)%; intake outdoor airflow temperature variation was assumed in the range of t_{ce} = (–30 to 10)°C. The ranges of exhaust airflow velocity in matrix passages and outdoor air stream to exhaust air stream specific heat capacity rate ratio variations were assumed on the basis of preliminary experiments: w_{h} = (2–8) m/s; $\overline{W}_{\text{c}}/\overline{W}_{\text{h}}$ = (1/2–3/2) (Anisimov, 1996; Anisimov and Fijałkowski, 2001).

The analysis of operating condition factors influence on index $\overline{F}_{\text{ice}}$ is undoubtedly decisive when choosing operating conditions, ruling out the possibility of units operation under frost arising conditions. In the proposed optimization problem statement the response function $\overline{F}_{\text{ice}}$ was considered a rigid restriction on investigated recuperator operating conditions. In this case the desired value of relative area of heat exchanger surface of possible frost arising is $\overline{F}_{\text{ice}} \leq 0$.

RESULTS AND DISCUSSION

Taking into account that the optimization carried out will be realized on the basis of taking the main components of integral effectiveness index into consideration, the initial stage of research was dedicated to clearing up of relationship characters between each of the selected differential quality coefficients and input parameters for the purpose of obtaining preliminary assessment of optimal operating conditions range variations for the recuperator. The results of the investigation carried out are shown in the Figure 3.

Analysis of experimental data detects substantial influence of inlet supply and exhaust airflow thermodynamic parameters on the values of all the proposed quality coefficients, which is largely set by the effect of released latent heat of condensation on the character of heat and mass exchange processes in recuperator matrix channels (Anisimov, 1996; Anisimov and Fijałkowski, 2001). As shown in Figure 3, the variation of exhaust airflow relative humidity in the low-humidity values region (φ_{he} < 30%) at the outdoor air temperature t_{ce} > –10°C have unsubstantial effect on characteristic effectiveness indexes values, because in these conditions coupled heat and water vapour transfer is realized under *dry surface mode* on almost the whole surface of the matrix. Raising of φ_{he} in the high relative humidity values region (φ_{he} > 45%) causes pronounced increase of heat and mass transfer efficiency (Figure 3a) at the expense of exhaust air latent heat recovery, which can be reach 48% of total heat transfer rate in the rear zone of the recuperator matrix surface ($\overline{Y} \rightarrow 1{,}0$) (Anisimov and Fijałkowski, 2001).

The relationships obtained indicate that it is possible to obtain high efficiency of the investigated heat exchanger and offer scope for estimation of variation range of recuperator optimum operating conditions. But the single-parameter optimization carried out led us to unsatisfactory results, connected with a discrepancy of selected characteristic effectiveness indexes' extremum (Figure 3), which naturally necessitated using compromised multi-criteria optimization methods on the basis of developing a generalized quality coefficient.

Different functions may be used for the mathematical description of the relationship between this kind of generalized efficiency coefficient and individual quality criteria. The generalization of the whole complex of contradictory individual optimization functions was carried out by means of creating an integral efficiency coefficient on the basis of using Harrington's multiplicative criterion (Harrington, 1965):

$$D = \prod_{i=1}^{n} d_i^{k_i}, \tag{1}$$

where d_i is the individual dimensionless quality coefficients; k_i the weights of individual efficiency coefficients, the sum of which is equal to 1.0.

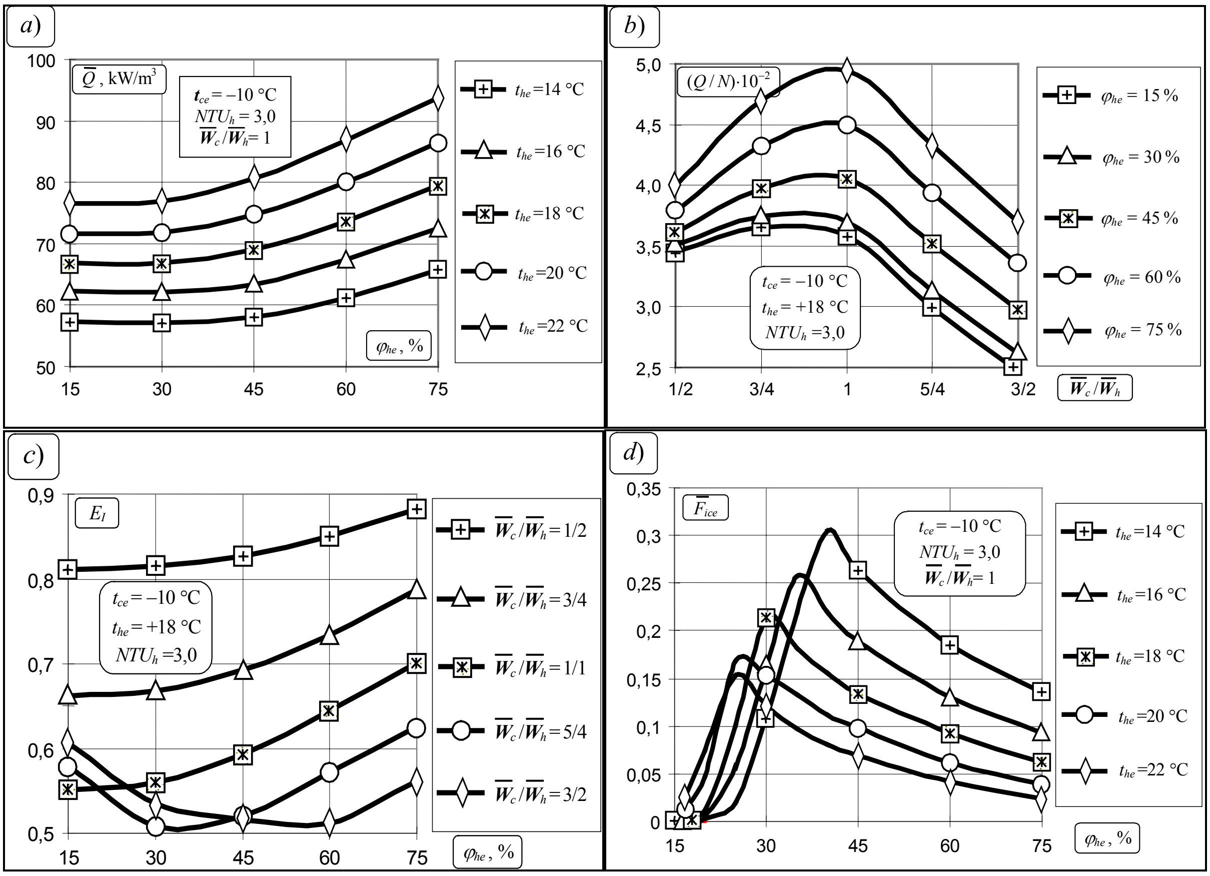

Figure 3 Influence of dimensionless operating conditions factors NTU_h, $\overline{W}_c/\overline{W}_h$ on effectiveness of heat and mass transfer in PPHE matrix under different initial airflow conditions.

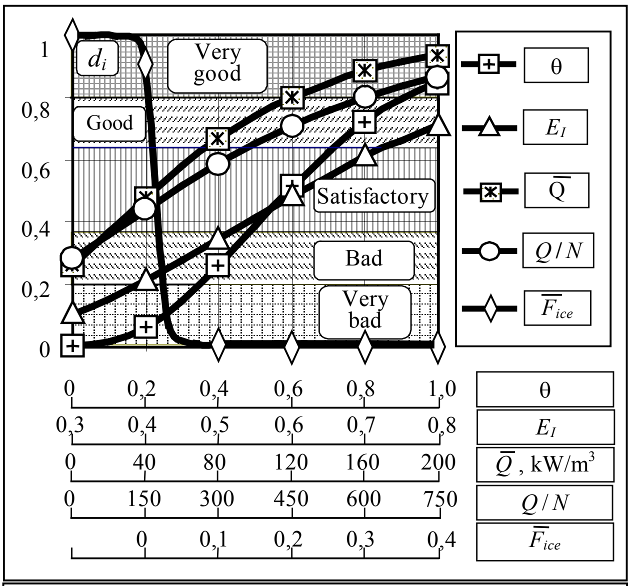

Figure 4 Preference scale of individual efficiency indexes.

Development of this kind of vector criterion requires corrective procedure of individual efficiency weights estimation and transformation of selected efficiency coefficients into dimensionless scale. In this connection we gave preference to the method of stochastic quality measurements (Bolotin et al., 1991; Anisimov et al., 2000).

This method gives possibility of using of different (very often contradictory) information and controlling quality of received information on the basis of the examination results. The results of individual efficiency indexes' conversion into dimensionless scale are presented in Figure 4.

Assigning the weights to the components of vector criterion D was carried out by experts on the basis of quality estimation of relationships between weights of local efficiency coefficients θ, E_i, $\bar{Q}$, Q/N, $\bar{F}_{\rm ice}$. For the purpose of rational examination making the form of results presentation was uniform:

$$\left(inf\ a_{ij}\ \leq\ a_{ij}\ \leq\ sup\ a_{ij}\right)\left|P_{ij}\right., \tag{2}$$

where $inf\ a_{ij}$, $sup\ a_{ij}$ are respectively estimation of lower and upper limits of weights ratio of local efficiency coefficients with probability P_{ij}.

Processing the information, received according to all the possible ratios of weights, was carried out with the help of a PC on the basis of methodology presented in the work by Bolotin et al. (1991). In consequence of examinations the weights of selected efficiency coefficients were received: $\bar{k}_\theta = (0{,}15 \pm 0{,}01)$; $\bar{k}_{E_i} = (0{,}16 \pm 0{,}01)$; $\bar{k}_{\bar{Q}} = (0{,}45 \pm 0{,}04)$; $\bar{k}_{Q/N} = (0{,}15 \pm 0{,}01)$; $\bar{k}_{\bar{F}_{ice}} = (0{,}09 \pm 0{,}01)$.

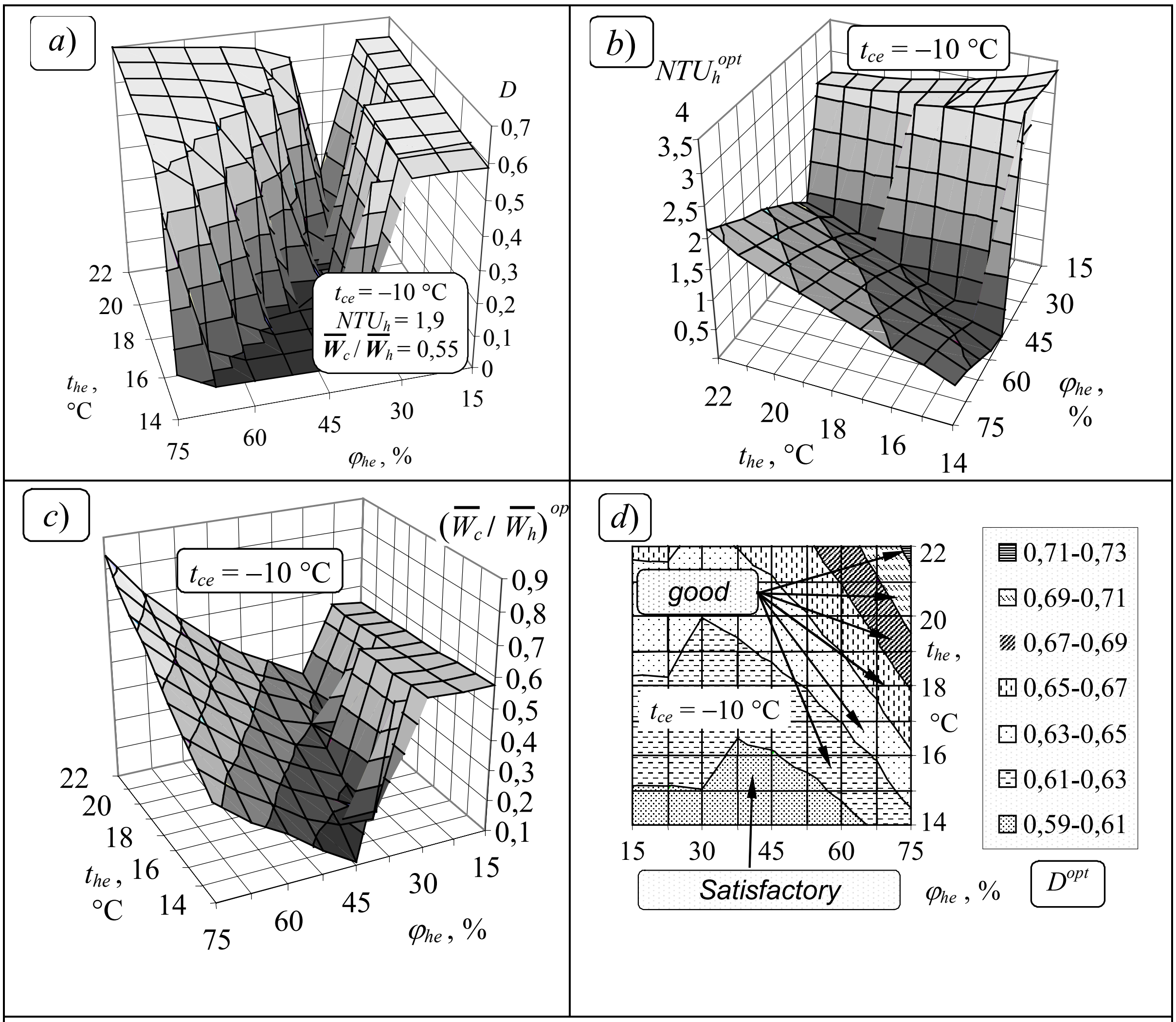

Figure 5 Optimal operating conditions and suitable climate zones assessment for investigated recuperator.

Computer simulations, carried out with the help of mathematical response surface models (Figure 5a) offered scope to determine optimal (according to Pareto) performance characteristics of PPHE, which were scored on Harrington scale of desirability and preference D^{opt} (Harrington, 1965), and generalize them in dimensionless form (Figure 5b,c). The results of the optimization research provided the possibility to estimate optimum operating conditions and suitable climatic zones for the investigated heat exchanger (Figure 5d).

NOMENCLATURE

c = specific heat capacity [J/(kg K)]; d = absolute humidity of air [kg/kg (g/kg)]; F = transfer area of matrix, exposed to air stream [m^2]; G = air mass flow rate [kg/s]; i = enthalpy of air–water vapour mixture, per unit mass of dry air [J/kg]; L_X = plate length in X direction [m]; L_Y = plate length in Y direction [m]; t = temperature [°C]; $\overline{W}$ -heat capacity rate = $\left(G \cdot c_p\right)$, W/K; X = axial coordinate along plate in direction of cold flow stream [m]; Y = axial coordinate along plate in direction of hot stream [m]; $\overline{X} = X/L_X$, $\overline{Y} = Y/L_Y$ -relative coordinates, dimensionless; α = sensible heat transfer coefficient [W/(m^2·K)]; φ = relative humidity, %.

Dimensionless Complexes

NTU = number of heat transfer units = $(\alpha \cdot F)/(G \cdot c_p)$.

Subscripts

c = cold air stream; e = state of air stream at the entrance of passage; h = hot air stream; o = state of air stream on exit from matrix; p = at constant pressure.

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