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Speciality paper

Poenostavljen model za popis dinamičnega odziva lamelnega prenosnika toplote

A Simplified Model of the Dynamic Response of a Finned-tube Heat Exchanger

BOGOMIL KANDUS - ALOJZ POREDOŠ

Določitev dinamičnega odziva lamelnega prenosnika toplote na temelju poenostavljenega matematičnega modela omogoča simuliranje njegovega delovanja v različnih razmerah in s tem pravilno povezavo za učinkovito delovanje v klimatizacijskem sistemu.

V članku je prikazan matematični model, ki omogoča, pri uporabi numeričnih metod, določitev dinamične karakteristike lamelnega prenosnika toplote, in sicer spremembo izstopne temperature zraka v odvisnosti od spremembe vstopne temperature vode. Rezultati računalniškega simuliranja, pridobljeni na temelju poenostavljenega matematičnega modela, so preverjeni z meritvami časovnega odziva lamelnega prenosnika toplote na spremembo vstopne temperature vode.

Ključne besede: prenosniki toplote, prenosniki lamelni, odziv dinamični, sistemi klimatizacijski

The study of the dynamic response of a finned-tube heat exchanger on the basis of a simplified mathematical model enables the simulation of its operation under various conditions and its correct installation in order to ensure efficient operation in an air-conditioning system.

The paper presents a mathematical model which enables the determination of the dynamic characteristics of a finned-tube heat exchanger with the use of numerical methods, i.e. the variation of outlet air temperature versus changes in inlet water temperature. The results of computer simulation obtained on the basis of a simplified mathematical model were verified by measuring the time response of the finned-tube heat exchanger to changes in inlet water temperature.

Keywords: heat exchangers, finned-tube exchangers, dynamic response, air-conditions systems

0 UVOD

Pri določanju delov klimatizacijskega sistema so potrebna tudi podrobnejša védenja o njihovih dinamičnih karakteristikah. To je še posebej pomembno v primeru, ko je vpliv določenega elementa v regulacijski zanki zelo velik.

Dinamična karakteristika hladilnega ali grelnega telesa klimatizacijskega sistema bistveno vpliva na zmožnost vzdrževanja temperature znotraj določenih mej v manjšem prostoru s časovno spremenljivim virom ali ponorom toplote, ali pa na zmožnost doseganja različnih temperatur v prostoru ob želenem temperaturnem gradientu.

Doseganje parametrov zraka v prostoru je prav gotovo, poleg dinamičnih karakteristik elementov, odvisno tudi od zgradbe in načina regulacije klimatizacijskega sistema. Vzdrževanje ali doseganje temperature v omejenem prostoru samo s prenosnikom toplote, ki deluje po načelu posrednega gretja ali hlajenja, je ena od cenovno ugodnih in tudi energetsko učinkovitih možnosti.

Dinamične analize lamelnih prenosnikov toplote oziroma matematični modeli se razlikujejo glede na njihovo konstrukcijo, vlogo v klimatizacijskem sistemu, medije oziroma agregatno stanje medijev. V določenih primerih pa upoštevajo tudi spremembo njihovih agregatnih stanj. Osnova za izdelavo dinamičnega modela prenosnika toplote je popis ustaljenega

0 INTRODUCTION

Determination of air-conditioning system parts requires a detailed knowledge of their dynamic characteristics. This is especially important in the cases when the influence of a certain element in the control loop is very large.

The dynamic characteristics of the heating/cooling unit of an air-conditioning system have a considerable influence on its ability to maintain temperature within a certain range, e.g. in a small room with a time-variable heat source or sink, or on its ability to achieve different room temperatures at the desired temperature gradient.

In addition to the dynamic characteristics of its elements, the achievement of certain air parameters in a room depends on the structure and method of control of the air-conditioning system. The maintenance or achievement of a certain temperature in a closed space solely through the use of heat exchangers operating on the principle of indirect heating/cooling is an inexpensive and energy-efficient option.

The dynamic analysis of finned-tube heat exchangers, i.e. their mathematical models, differs with respect to their design, role in the air-conditioning system, the heating/cooling media or their aggregate state; in certain cases it also takes into account changes in their aggregate states. Dynamic models of heat exdelovanja [4]. Primerno je, da pri dinamičnem modeliranju začnemo najprej s preprostimi modeli [1], ki jih glede na želene rezultate dopolnjujemo ([3] in [5]).

Pri analizi dinamičnega odziva prenosnika toplote smo želeli pridobiti tudi informacije o dogajanjih znotraj obravnavanega sistema, zato smo za reševanje matematičnega modela uporabili numerične metode. Namen analize z numeričnim modeliranjem je bil tudi ugotoviti, do kakšne stopnje lahko poenostavimo matematični model, da bomo dobili še ustrezne rezultate pri simuliranju dinamičnega delovanja prenosnika toplote. V našem primeru smo za analizo izbrali standardni lamelni prenosnik, z vodo kot delovnim medijem za hlajenje oziroma gretje vlažnega zraka. Njegovo delovanje smo analizirali glede na spremembe izstopne temperature zraka v odvisnosti od spremembe vstopne temperature vode v področju občutnega hlajenja vlažnega zraka.

1 USTALJENI MODEL PRENOSNIKA TOPLOTE

Že pri dimenzioniranju prenosnika toplote v ustaljenem stanju naletimo na problem določitve njegove toplotne moči, na katero poleg fizikalnih parametrov, kakršni sta toplotna prevodnost in toplotna prestopnost na strani zraka ali vode, bistveno vpliva tudi konstrukcija. Obravnavo ustaljenega stanja prenosnika toplote lahko dodatno zaplete še pojav kondenzacije vodne pare iz zraka na hladni površini.

Osnova za izdelavo modela za popis dinamike prenosnika toplote je določitev krajevne lestvice, na podlagi katere bomo opazovali sistem. Za osnovni element prenosnika toplote lahko izberemo delček cevi in njemu pripadajoče rebro, ta je določen z geometrijsko obliko prenosnika toplote.

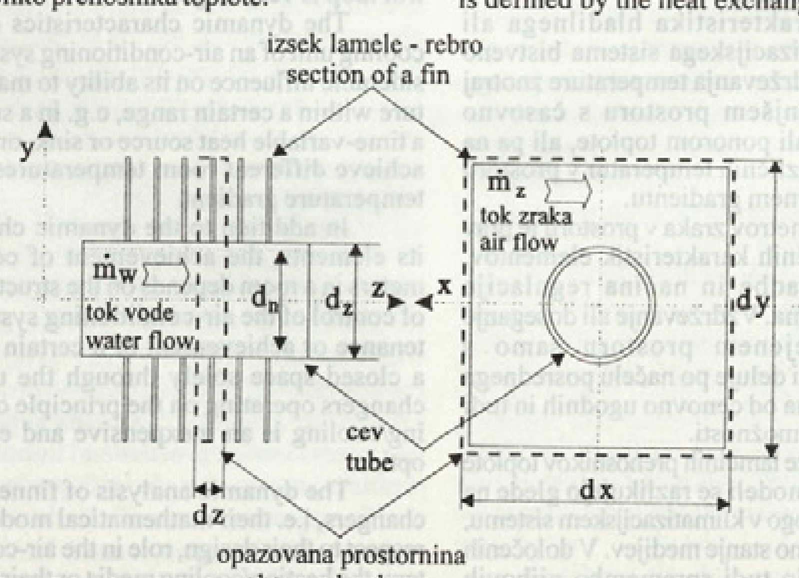
changers are based on the definition of their steady-state operation [4]. It is reasonable for dynamic modelling to begin with a simplified model [1], which may be upgraded with respect to the desired results ([3] and [5]).

In analysing the dynamic response of a heat exchanger, we wished to obtain information on processes which take place inside the studied system, therefore numerical methods were used to solve the mathematical model. The goal of analysis by numerical modelling was also to establish to what degree a mathematical model can be simplified while still obtaining suitable results in the simulation of the dynamic operation of heat exchangers. In our case, a standard finned-tube heat exchanger was used for analysis, with water as the working medium for the cooling and heating of humid air. It was analysed with regard to changes in output air temperature versus changes in input water temperature in the sensible cooling of humid air.

1 STEADY-STATE MODEL OF A HEAT EXCHANGER

During the dimensioning of heat exchangers in the steady state, one encounters the problem of determining their heat flux, which among other physical parameters such as the heat conductivity and heat transfer coefficient on the air side or on the water side is considerably influenced by their design. The study of the steady state of heat exchangers may be additionally complicated by the condensation of water vapour from air on cool surfaces.

The determination of a spatial scale on the basis of which the system will be observed serves as the foundation for a model of heat exchanger dynamics. A tube segment and its corresponding fin can be selected as the basic element of a heat exchanger and is defined by the heat exchanger geometry.



Sl. 1. *Osnovni element prenosnika toplote*
Fig. 1. *Basic element of a heat exchanger*

V primeru, ko na osnovnem elementu ne pride do kondenzacije vodne pare iz zraka na hladni površini, in če uvedemo srednjo temperaturo delca cevi in rebra T_c, lahko matematični model močno poenostavimo. Ob predpostavki, da je stik med rebrom in cevjo homogen ter omogoča neoviran prenos toplote, lahko obravnavamo delec cevi in rebra kot homogeno enoto z ekvivalentno maso in temperaturno prevodnostjo. Energijsko bilanco osnovnega elementa prenosnika toplote (sl. 2) lahko določimo s sistemom treh linearnih enačb s tremi neznankami $T_{z,i}$, $T_{w,i}$, T_c. Na strani zraka lahko zapišemo:

The mathematical model can be considerably simplified in the case of no condensation of water vapour from air on a cool surface of the basic element, and by introducing mean temperature of a tube and fin section T_c. With the assumption that the junction between the fin and the tube is homogenous and enables unimpeded heat transfer, the tube and fin section can be treated as a homogeneous unit, with equivalent mass and thermal diffusivity. The energy balance of the basic element of a heat exchanger (Fig. 2) can be determined using a system of three linear equations with three unknowns, $T_{z,i}$, $T_{w,i}$, T_c. For the air side it can be written that:

$$\dot m_{z,i} \cdot c_{p,z} \cdot \left(T_{z,v} - T_{z,i}\right) = \alpha_z \cdot S_{z,i} \cdot \left(\frac{T_{z,v} + T_{z,i}}{2} - T_c\right) \quad (1),$$

kjer je $c_{p,z}$ specifična toplota vlažnega zraka. Energijska bilanca na strani vode je:

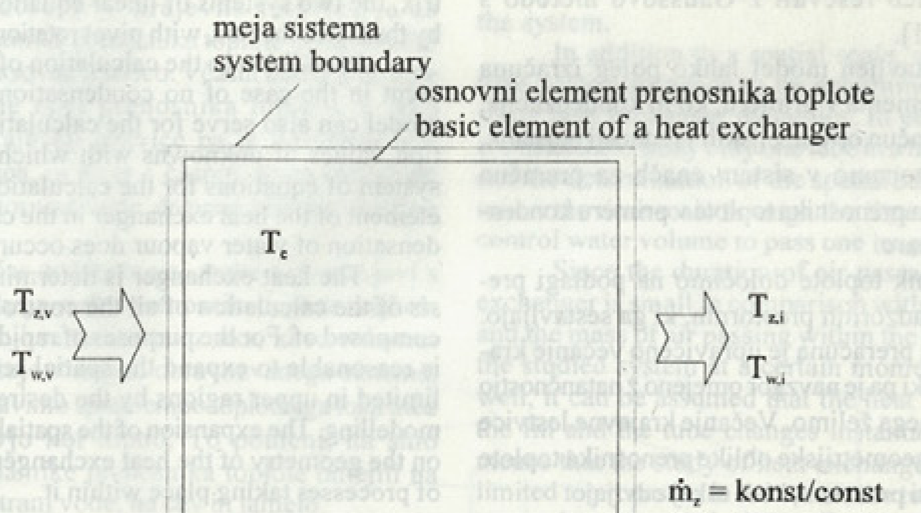
where $c_{p,z}$ is the specific heat of humid air. The energy balance for the water side is:

$$\dot m_w \cdot c_{p,w} \cdot \left(T_{w,v} - T_{w,i}\right) = \alpha_w \cdot S_{w,i} \cdot \left(\frac{T_{w,v} + T_{w,i}}{2} - T_c\right) \quad (2).$$

Velja tudi enakost bilanc na strani zraka in vode:

The balances for air and water side are:

$$\dot m_{z,i} \cdot c_{p,z} \cdot \left(T_{z,v} - T_{z,i}\right) = \dot m_z \cdot c_{p,w} \cdot \left(T_{w,i} - T_{w,v}\right) \quad (3).$$



Sl. 2. *Vstopne in izstopne veličine pri prenosu toplote prek mej osnovnega elementa prenosnika toplote*

Fig. 2. *Input and output parameters in heat transfer across the boundaries of the basic element of a heat exchanger*

Sistem treh enačb lahko zapišemo v obliki matrične enačbe:

The system of three equations can be written in the form of a matrix equation:

$$A * x = b \quad , \quad A = \begin{bmatrix} A_{1,1} & A_{1,2} & A_{1,3} \\ A_{2,1} & A_{2,2} & A_{2,3} \\ A_{3,1} & A_{3,2} & A_{3,3} \end{bmatrix} \quad b = \begin{bmatrix} A_{1,4} \\ A_{2,4} \\ A_{3,4} \end{bmatrix} \quad (4).$$

pri čemer je x ($T_{z,i}$, $T_{w,i}$, T_c), koeficienti A_{ij} pa pomenijo deleže enačb, ki množijo neznane veličine:

where x is ($T_{z,i}$, $T_{w,i}$, T_c) and coefficients A_{ij} represent the terms which multiply the unknowns:

$$\begin{aligned}
A_{1,1} &= \dot{m}_{z,i}.c_{p,z} + \frac{\alpha_z.S_{z,i}}{2}\\
A_{1,2} &= 0\\
A_{1,3} &= -\alpha_z.S_{z,i}\\
A_{1,4} &= \dot{m}_{z,i}.c_{p,z} + \frac{\alpha_z.S_{z,i}}{2}\\
A_{2,1} &= \dot{m}_w.c_{p,w} + \frac{\alpha_w.S_{w,i}}{2}\\
A_{2,2} &= 0\\
A_{2,3} &= -\alpha_w \cdot S_{w,i}\\
A_{2,4} &= \dot{m}_w.c_{p,w} + \frac{\alpha_w.S_{w,i}}{2}\\
A_{3,1} &= \dot{m}_{z,i}.c_{p,z}\\
A_{3,2} &= \dot{m}_w.c_{p,w}\\
A_{3,3} &= 0\\
A_{3,4} &= T_{z,v}.\dot{m}_{z,i}.c_{p,z} + T_{w,y}.\dot{m}_w \cdot c_{p,w}
\end{aligned} \tag{5}$$

Indeks i pri nekaterih veličinah enačb (1) do (5) pomeni zaporedno številko nadzorne prostornine.

Sistem linearnih enačb, zapisan v obliki matrike, lahko rešimo z ustrezno neposredno ali iteracijsko metodo. Glede na velikost matrike smo sistema linearnih enačb reševali z Gaussovo metodo s pivotiranjem [1].

Poenostavljen model lahko poleg izračuna osnovnega elementa v primeru, ko ni kondenzacije, rabi tudi za izračun orientacijskih vrednosti neznank, s katerimi vstopamo v sistem enačb za preračun osnovnega dela prenosnika toplote v primeru kondenzacije vodne pare.

Prenosnik toplote določimo na podlagi preračuna vseh nadzornih prostornin, ki ga sestavljajo. Zaradi hitrosti preračuna je upravičeno večanje krajevne lestvice, ki pa je navzgor omejeno z natančnostjo popisa, kakršnega želimo. Večanje krajevne lestvice je odvisno od geometrijske oblike prenosnika toplote in intenzivnosti procesov, ki se tukaj odvijajo.

2 DINAMIČNI ODZIV PRENOSNIKA TOPLOTE

Geometrijska oblika prenosnikov toplote je optimirana glede na čim večje toplotne prehodnosti, minimalnih dimenzij in čim manjših tlačnih izgub tekočin. V primeru, kadar je pomembna hitrost časovnega odziva prenosnika toplote, je poleg vpliva njegove mase treba poznati tudi vpliv pretoka hladilne in grelne tekočine na dinamiko. Pri obravnavanju dinamičnega odziva ni dovolj, da poznamo hitrost širjenja toplote prek cevi in rebra oziroma po tekočini v cevi in na zunanji strani, ampak sta pomembna tudi

The index i in certain parameters of equations (1) to (5) indicates the sequential number of the control volume.

The system of linear equations written in matrix form can be solved using an appropriate direct or iterative method. With regard to the size of the matrix, the two systems of linear equations were solved by the Gauss method, with pivot rotation (1).

In addition to the calculation of the basic element in the case of no condensation, a simplified model can also serve for the calculation of orientation values of unknowns with which we enter the system of equations for the calculation of the basic element of the heat exchanger in the case when condensation of water vapour does occur.

The heat exchanger is determined on the basis of the calculation of all the control volumes it is composed of. For the purposes of rapid calculation, it is reasonable to expand the spatial scale, but this is limited in upper regions by the desired accuracy of modelling. The expansion of the spatial scale depends on the geometry of the heat exchanger and intensity of processes taking place within it.

2. DYNAMIC RESPONSE OF A HEAT EXCHANGER

The geometry of heat exchangers is optimised to ensure the highest possible overall heat transfer, minimum dimensions and minimum pressure loss in the fluids. In the case when the time response speed of a heat exchanger is important, the influence of the flow of the cooling/heating fluid on its dynamics needs to be known in addition to the influence of its mass. In studying the dynamic response, it is not enough to know the speed of heat transfer through tubes and fins or through the fluid in the tube and on the outpot in čas zadrževanja tekočine v območju prenosnika. Običajno so lamelni prenosniki izvedeni z večjim številom vstopov vode, ni pa nujno, da so vse cevne poti vode med seboj enake, to pa še dodatno otežuje njihovo obravnavo.

Vpliv pretokov tekočin ter mase prenosnika toplote na dinamični odziv se spreminja v odvisnosti od geometrijske oblike cevi in lamel ter hitrosti in pretočnih razmer tekočin.

Pri običajnem kanalskem prenosniku toplote v klimatizacijskem sistemu, pri katerem je hladilna ali grelna tekočina voda, velja:

- čas zadrževanja zraka v prenosniku je veliko manjši od časa zadrževanja delca vode,
- masa praznega prenosnika je približno enaka masi vode v ceveh,
- proces prevoda toplote prek cevi in rebra je veliko hitrejši od gibanja vode v prenosniku toplote.

Da bi okvirno popisali dinamiko prenosnika toplote, smo najprej izdelali preprost model. Zapleten je že popis dogajanj na prenosniku toplote v ustaljenem stanju, ki zahteva posebno obravnavo vsakega geometrijsko različnega primera, teh pa je v praksi veliko. Pri dinamičnem modelu je potrebnih še več poenostavitev, vendar lahko kljub temu s pravilnim postopkom dosežemo zadovoljiv popis sistema.

Poleg določitve krajevne lestvice je za obravnavo dinamike prenosnika toplote treba določiti tudi ustrezno časovno lestvico. Včasih lahko zadostuje obravnava ene cevi prenosnika toplote, s tako določitvijo krajevne lestvice pa je določena tudi časovna lestvica, in sicer s časom, ki ga potrebuje nadzorna prostornina vode, da prepotuje eno dolžino cevi.

Ker je čas zadrževanja zraka v primerjavi s časom zadrževanja vode v prenosniku toplote majhen, hkrati pa je majhna tudi masa zraka, ki se v danem trenutku zadržuje v mejah obravnavanega sistema, lahko predpostavimo spremembo toplotnega toka med lamelo in cevjo kot hipno. To pomeni, da smo obravnavo dinamike prenosnika toplote omejili na dogajanja na strani vode, na cev in lamelo.

Kakor smo že zapisali, smo pri ustaljenem modelu osnovnega elementa določili srednjo temperaturo cevi in rebra. Ker za obnašanje navidezne homogene nadzorne prostornine velja, da je upornost prestopu toplote veliko večja, kakor upornost prevoda toplote, kar določa majhno Biotovo število (sl. 3), lahko za popis časovne odvisnosti temperature homogenega telesa ob spremembi temperature vode uporabimo metodo združenega delca [2]. Definiramo brezdimenzijsko temperaturo:

side; the path and time the fluid stays in the heat exchanger are also relevant. Finned-tube heat exchangers are usually designed with several water inputs. It is also not necessary for all tube lengths to be equal, which additionally increases the difficulty of their study.

The influence of fluid flows and heat exchanger mass on its dynamic response varies depending on the tube and fin geometry and the speed and flow conditions of the fluids.

In a standard channel heat exchanger in an air-conditioning system with water as the cooling/heating fluid,

- the duration of passage of air in the heat exchanger is much shorter than that of water,
- the mass of the empty heat exchanger is approximately equal to the mass of water in the tubes,
- the process of heat transfer through tubes and fins is much more rapid than the movement of water through the heat exchanger.

In order to give an overall description of heat exchanger dynamics, a simple model was made. The description of processes in a steady-state heat exchanger is complex and requires special treatment of each specific geometric case, which are numerous in practice. In the dynamic model, even more simplifications are needed, but in spite of this a correct approach can yield a satisfactory description of the system.

In addition to a spatial scale, an appropriate time scale also needs to be determined in order to study heat exchanger dynamics. In certain cases, it is sufficient to study only one tube in a heat exchanger, and the determination of the spatial scale also determines the time scale through the time required for a control water volume to pass one length of the tube.

Since the duration of air passage in the heat exchanger is small in comparison with that of water, and the mass of air passing within the boundaries of the studied system at a certain moment is small as well, it can be assumed that the heat flow between the fin and the tube changes instantaneously. This means that the study of heat exchanger dynamics is limited to processes in the water, the tube and the fin.

As was noted above, the mean temperature of the tube and fin was determined in the steady-state model of the basic element. Since it applies to the behaviour of apparent homogeneous control volume that the resistance to heat transfer is much greater than that to heat conduction, which is determined by a small Biot number (Fig. 3), a lumped capacitance method can be used for the description of the time variation of the temperature of a homogeneous body due to changes in water temperature [2]. Non-dimensional temperature is defined as follows:

$$\Theta = \frac{T - T_\infty}{T_A - T_\infty} = e^{-\left(\frac{\alpha.A}{\rho.V.c}\right).t} \quad (6)$$

ali

or

$$\Theta = e^{-Bi.Fo} \quad (7),$$

pri čemer je Biotovo število Bi, ki ga določa razmerje upornosti prevoda X/λ in prestopa toplote 1/α:

where the Biot number Bi, which is determined by the ratio of resistance to heat conduction X/λ to resistance to heat transfer 1/α is:

$$Bi = \frac{\alpha . X}{\lambda} \quad (8).$$

Fourierjevo število Fo pomeni brezdimenzijski čas in poleg Biotovega števila karakterizira procese neustaljenega prehoda toplote:

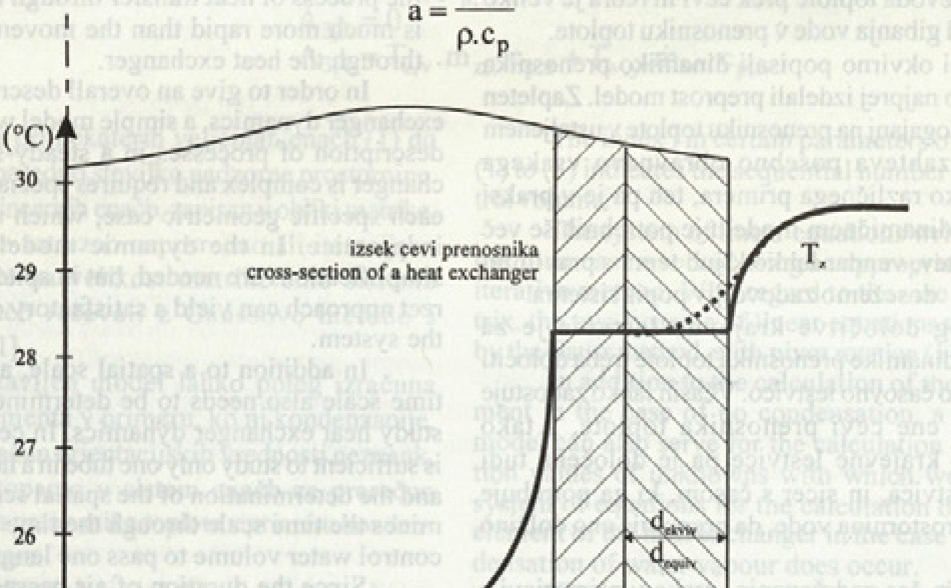
The Fourier number Fo represents non-dimensional time and, along with Biot number characterises the processes of non-steady-state overall heat transfer:

$$Fo = \frac{\alpha . t}{X^2} \quad (9),$$

temperaturna prevodnost a pa je enaka:

while thermal diffusivity a equals:

$$a = \frac{\lambda}{\rho . c_p} \quad (10).$$



Sl.3. *Enodimenzijsko temperaturno polje v nadzorni prostornini prenosnika toplote v ustaljenem stanju*

Fig. 3. *Unidimensional temperature field in a control volume of a heat exchanger in steady state*

Energijsko bilanco osnovnega dela prenosnika toplote v koraku Δt lahko zapišemo z enačbo:

The energy balance of the basic element of a heat exchanger in the interval Δt can be written:

$$\Delta Q_z + \Delta Q_{c,r} + \Delta Q_w = 0 \quad (11).$$

Če zanemarimo prevod toplote med sosednjimi nadzornimi prostorninami vode, cevi in lamele, dobimo sliko časovno odvisnega enodimenzionalnega prehoda toplote med vodo in navideznim homogenim delom cevi in rebra. Prehod toplote iz rebra oziroma cevi na zrak smo že prej predpostavili kot hipen proces.

3 RAČUNALNIŠKO SIMULIRANJE DINAMIČNEGA ODZIVA PRENOSNIKA TOPLOTE

Pri reševanju matematičnega modela prenosnika toplote, ki je sestavljen iz končnega števila osnovnih elementov, zaradi želene natančnosti, nadaljnje večanje krajevne lestvice ni mogoče. V našem primeru smo obravnavali običajen šestvrstni kanalski prenosnik toplote s štirinajstimi cevmi po višini in valovitimi lamelami. Prenosnik toplote ima šestnajst vstopov in izstopov vode. Cevne povezave so izdelane po načelu protitoka vode in zraka s tem, da so posamezne cevne povezave med seboj različne.

Zaradi predpostavke o homogenem hitrostnem in temperaturnem polju po prerezu prenosnika smo lahko računalniško simuliranje izvajali za eno cev v vrsti, razmere v vodnem toku pa so se spreminjale vzdolž cevi in v toku zraka od prve do zadnje cevne vrste. Z obravnavo le enega dela prenosnika toplote, ki je bil razdeljen na večje število nadzornih prostornin, smo dobili časovni odziv celotnega prenosnika toplote.

Razdelitev obravnavanega prenosnika na cevne vrste je prikazana na sliki 4. Glede na protitok vode in zraka ni mogoč neposreden preračun posameznih nadzornih prostornin eno za drugo, ampak je treba sisteme enačb elementov reševati z uporabo posrednih metod za vsako periodo časa, ki je določena s časovno lestvico.

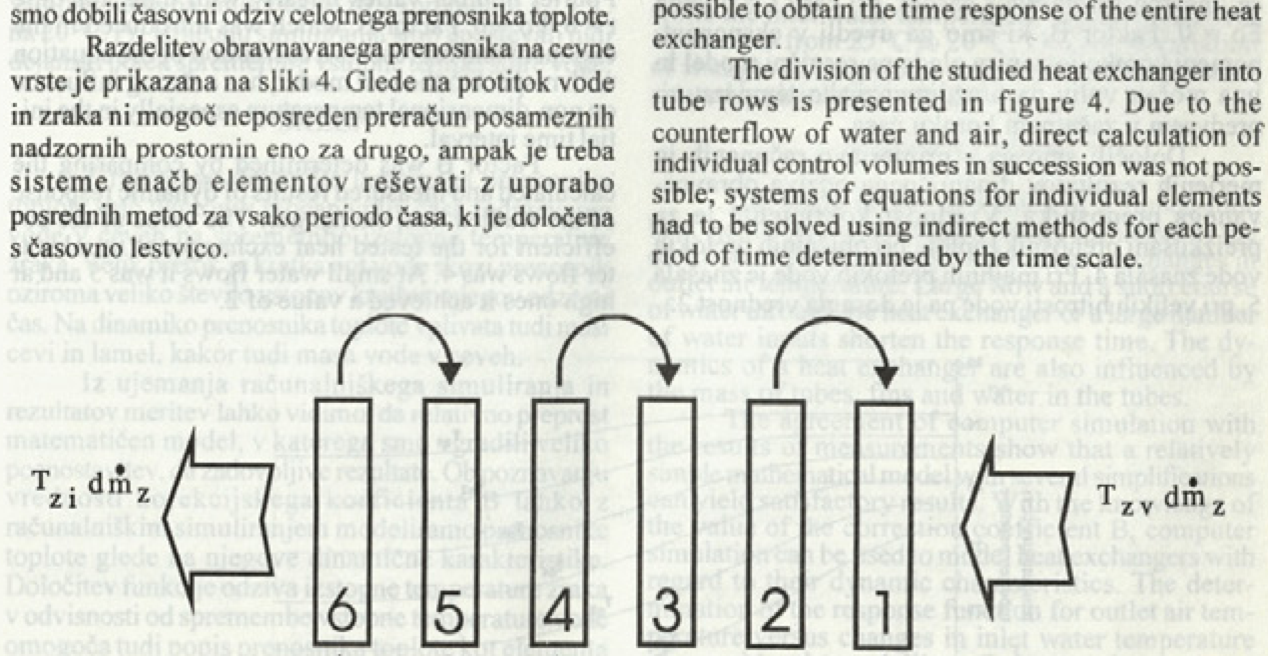
If heat conduction between adjoining control volumes of water, the tube and the fin is neglected, a picture of time-dependent unidimensional overall heat transfer between water and the apparent homogeneous part of the tube and fin is obtained. Overall heat transfer from the fin or tube to air has already been assumed to be an instantaneous process.

3 COMPUTER SIMULATION OF THE DYNAMIC RESPONSE OF A HEAT EXCHANGER

In solving a mathematical model of a heat exchanger, which consists of a finite number of basic elements, a further expansion of the spatial scale is not possible due to the desired accuracy. In our case, a standard 6-row channel heat exchanger with fourteen tubes along its height and corrugated fins was studied. The heat exchanger has sixteen water inlets and sixteen outlets. Tube connections were made on the basis of the principle of counterflow of water and air, and individual tube connections were different.

Due to the assumption of homogeneous speed and temperature fields over the cross-section of the heat exchanger, computer simulation could be performed for one tube per row, while conditions in the water flow varied along the tube and the air flow from the first tube row to the last tube row. By studying only one part of the heat exchanger, which was divided to a greater number of control volumes, it was possible to obtain the time response of the entire heat exchanger.

The division of the studied heat exchanger into tube rows is presented in figure 4. Due to the counterflow of water and air, direct calculation of individual control volumes in succession was not possible; systems of equations for individual elements had to be solved using indirect methods for each period of time determined by the time scale.



Sl. 4. *Poenostavljen model prenosnika toplote*
Fig. 4. *Simplified model of the heat exchanger*

Z vpeljavo navidezne nadzorne prostornine cevi in rebra ter navidezne srednje temperature cevi smo lahko z računalniškim simuliranjem določili časovno odvisnost spreminjanja temperature cevi po globini prenosnika toplote ob spremembi vstopne temperature vode (sl. 5). Temperaturne črte povprečne temperature cevi v vrsti potrjujejo logičnost delovanja simulirnega modela. Ker je cev, označena s številko 1, zadnja na poti nadzorne prostornine vode, je zakasnitev spremembe temperature cevi na njej največja. Zaradi spremenjenih temperaturnih polj v prenosniku, ki nastanejo zaradi spremembe vstopne temperature vode, se največja in najhitrejša temperaturna sprememba dogodi na šesti cevi.

V Laboratoriju za hladilno tehniko na Fakulteti za strojništvo v Ljubljani smo opravili meritve dinamičnega odziva modeliranega prenosnika. Postavili smo eksperimentalno napravo, kjer smo zagotovili enake robne pogoje, kakršne smo uporabili pri simuliranju.

Za ujemanje med računalniškim modelom in rezultati meritev smo uvedli v metodo združenega delca korekcijski koeficient B. S tem smo prilagodili eksponentno funkcijo brezdimenzijske temperature po enačbi (6):

By introducing the apparent control volume of the tube and the fin and apparent mean temperature of the tube, it was possible to determine the time dependence of the variation of tube temperature along the depth of the heat exchanger with the change of inlet water temperature by computer simulation (Fig. 5). The temperature lines of mean tube temperature in one row confirm the logic of the functioning of the simulation model. Since the tube designated by No. 1 is the last one on the course of the control water volume, the delay of change in tube temperature in it is the longest. Due to changed temperature fields in the heat exchanger which result from changes in the inlet water temperature, the largest and the fastest temperature change occurs on the sixth tube.

The Laboratory for Refrigeration at the Faculty of Mechanical Engineering in Ljubljana performed measurements of the dynamic response of the modelled heat exchanger. An experimental set-up was constructed and equal boundary conditions to those used in the simulation were ensured.

To ensure agreement between the computer model and the results of measurements, a correction coefficient B was introduced in the lumped capacitance method. This served to modify the exponential function of non-dimensional temperature according to equation (6):

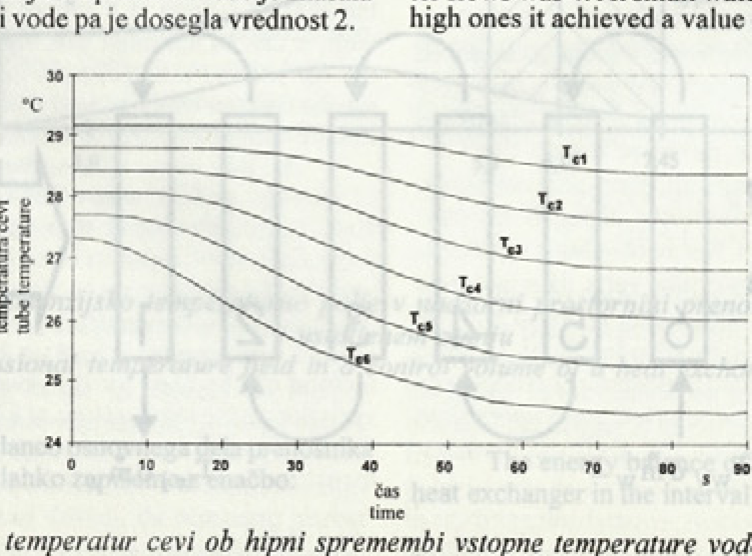
$$\frac{T_c - T_{c,\infty}}{T_{c,i} - T_{c,\infty}} = e^{\frac{-Bi.Fo}{B}} \qquad (12).$$

Pogoj za uporabo metode združenega delca je majhno Biotovo število (Bi << 1). Fourierjevo število se linearno spreminja s časom, pri času t = 0 velja Fo = 0. Faktor B, ki smo ga uvedli v eksponent, pomeni korekcijo zapisa glede na resnični model in ima močan vpliv na brezdimenzijsko temperaturo predvsem v začetnem koraku časa.

Določili smo ga s primerjavo računanih in merjenih rezultatov dinamičnega odziva obravnavanega prenosnika. Vrednost koeficienta je za preizkušani prenosnik toplote pri običajnih pretokih vode znašala 4. Pri majhnih pretokih vode je znašala 5, pri velikih hitrosti vode pa je dosegla vrednost 2.

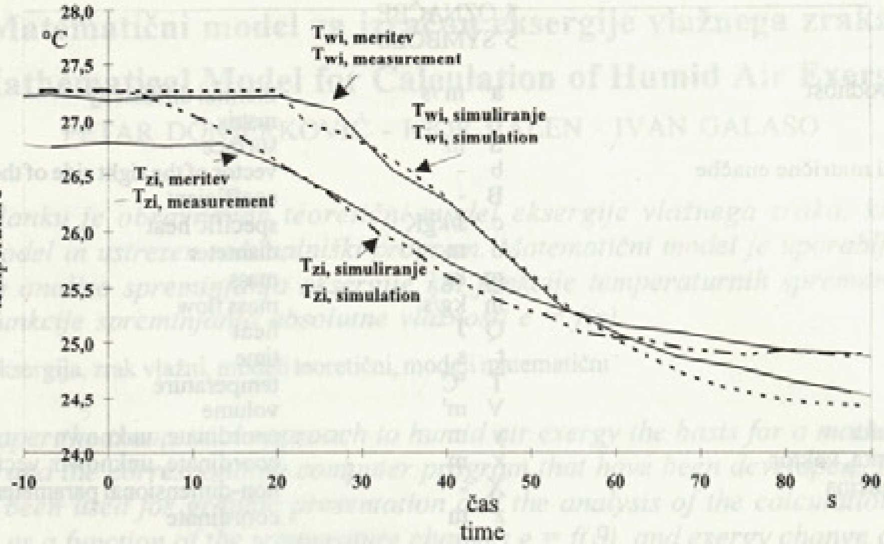
A small Biot number (Bi << 1) is a condition for the use of the lumped capacitance method. The Fourier number varies linearly with time; for time t = 0, Fo = 0. Factor B, which was introduced in the exponent and represents a correction of the equation with respect to the real model, has a strong influence on non-dimensional temperature especially in the initial time interval.

Factor B was determined by comparing the calculated and measured results of dynamic response of the studied heat exchanger. The value of the coefficient for the tested heat exchanger at usual water flows was 4. At small water flows it was 5 and at high ones it achieved a value of 2.



Sl. 5. *Sprememba temperatur cevi ob hipni spremembi vstopne temperature vode iz 25 °C na 20 °C*

Fig. 5. *Variation of tube temperature with a instantaneous change of inlet water temperature from 25 °C to 20 °C*



Sl. 6. *Prikaz meritve računalniškega simuliranja dinamičnega odziva lamelnega prenosnika toplote na hipno spremembo vstopne temperature vode s 25 °C na 20 °C*

Fig. 6. *Presentation of measurements and computer simulation of the dynamic response of a finned-tube heat exchanger to an instantaneous change in inlet water temperature from 25 °C to 20 °C*

Ujemanje med računalniškim simuliranjem in meritvijo prenosnika toplote je prikazano na sliki 6. Do razlik med simuliranjem in meritvijo prihaja že v ustaljenem stanju prenosnika, vendar so razlike absolutno majhne in ne vplivajo na popis dinamike odziva, tako da jih lahko zanemarimo.

Rezultati v diagramu na sliki 6 veljajo za temperaturo vstopnega zraka 30 °C, temperaturo vstopne vode pa smo v času 10 s spremenili s 25 °C na 20 °C. Pri izračunu simuliranja smo upoštevali tudi dejanski potek spremembe vstopne temperature vode.

4 SKLEP

Z raziskavo dinamike lamelnega prenosnika toplote smo ugotovili močan vpliv časa zadrževanja vode v ceveh na spremembo izstopne temperature zraka. Velik pretok in kratka pot vode skozi prenosnik oziroma veliko število vstopov krajšajo njegov odzivni čas. Na dinamiko prenosnika toplote vplivata tudi masi cevi in lamel, kakor tudi masa vode v ceveh.

Iz ujemanja računalniškega simuliranja in rezultatov meritev lahko vidimo, da relativno preprost matematičen model, v katerega smo vgradili veliko poenostavitev, da zadovoljive rezultate. Ob poznavanju vrednosti korekcijskega koeficienta B lahko z računalniškim simuliranjem modeliramo prenosnike toplote glede na njegove dinamične karakteristike. Določitev funkcije odziva izstopne temperature zraka v odvisnosti od spremembe vstopne temperature vode omogoča tudi popis prenosnika toplote kot elementa regulacijske zanke.

Dobljeni rezultati so nujni podatki za gradnjo regulacijskih sistemov pri vodenju klimatizacijskih naprav, katerih ključni elementi so lamelni prenosniki toplote v vlogi grelnika ali hladilnika zraka, in tako prispevajo k uspešnemu vzdrževanju stanja zraka v omejenem prostoru s spreminjanjem temperature tekočine v prenosniku toplote.

The agreement between computer simulation and measurements of the heat exchanger is presented in figure 6. Differences between simulation and measurements occur already in the steady state of the heat exchanger, but they are very small in absolute terms and do not affect the description of the response dynamics, and can therefore be neglected.

The results presented in the diagram in figure 6 are stated for an inlet air temperature of 30 °C, while the inlet water temperature was changed over 10 seconds from 25 °C to 20 °C. The actual variation of changes of inlet water temperature was also considered in simulation calculations.

4 CONCLUSION

The study of the dynamics of a finned-tube heat exchanger established a strong influence of the duration of water passage in the tubes on changes in outlet air temperature. Large flow and a short course of water through the heat exchanger or a large number of water inputs shorten the response time. The dynamics of a heat exchanger are also influenced by the mass of tubes, fins and water in the tubes.

The agreement of computer simulation with the results of measurements show that a relatively simple mathematical model with several simplifications can yield satisfactory results. With the knowledge of the value of the correction coefficient B, computer simulation can be used to model heat exchangers with regard to their dynamic characteristics. The determination of the response function for outlet air temperature versus changes in inlet water temperature also enables the modelling of a heat exchanger as an element of the control loop.

The obtained results are essential data for the design of control systems for air-conditioning devices in which finned-tube heat exchangers are crucial elements as air heaters/coolers and thus contribute to a successful maintenance of the state of air in a closed space by changing the temperature of the fluid in the heat exchanger.

5 OZNAČBE
5 SYMBOLS

temperaturna prevodnost	a	m^2/s	thermal diffusivity
matrika	A	-	matrix
površina	S	m^2	surface
vektor desne strani matrične enačbe	b	-	vector of the right side of the matrix equation
koeficient	B	-	coefficient
specifična toplota	c	J/kgK	specific heat
premer	d	m	diameter
masa	m	kg	mass
masni pretok	$\dot{m}$	kg/s	mass flow
toplota	Q	J	heat
čas	t	s	time
temperatura	T	°C	temperature
prostornina	V	m^3	volume
koordinata, neznanka	y	m	coordinate, unknown
koordinata, neznanka, vektor	x	m	coordinate, unknown, vector
brezdimenzijska veličina	X	-	non-dimensional parameter
koordinata	z	m	coordinate
toplotna prestopnost	α	W/m^2K	heat transfer coefficient
debelina	δ	m	thickness
razlika	Δ	-	difference
brezdimenzijska temperatura	Θ	-	non-dimensional temperature
gostota	ρ	kg/m^3	density
toplotna prevodnost	λ	W/mK	thermal conductivity
Biotovo število	Bi	-	Biot number
Fourierjevo število	Fo	-	Fourier number

Okrajšave in indeksi / Abbreviations and indexes

cev, površina	c	tube, surface
delec	d	lumped capacitance section basic element
izstop, števnik	i	outlet, enumerator
števnik	j	enumerator
števnik	k	enumerator
notranji	n	inner
konstantni tlak	p	constant pressure
rebro	r	fin
vstop	v	inlet
voda	w	water
zrak, zunanji	z	air, outer
neskončno	∞	infinity

6 LITERATURA
6 REFERENCES

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