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CALCULATION OF PERFORMANCE INDICATORS FOR HEAT PIPES RECOVERY UNITS WHICH OPERATE IN GAS-GAS MODE

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Abstract: *Comparing different constructive solutions to the same heat load and the same power consumption for heating by circulating heat recovery is performed using power quality index. This is an independent variable that expresses the heat flux transmitted at a mean temperature difference of 1K for a 1kW power consumption for heating through circulating device. Performance indices of the heat recovery devices evaluate the effectiveness of this devices considering the technical performance of a specific constructive solutions.*

Key words: *exergy efficiency, heat transfer units, heat recovery efficiency.*

1. Introduction

It is obvious that the development of a heat recovery system involves costs that influences the total investment cost. Therefore, in the opportunity analysis of the development of the heat recovery system it is necessary to introduce both economic and energy efficiency indicators.

In order to perform fast and accurate calculations of performance indices for heat recovery units with heat pipes operating in gas-gas system, the authors proposes in this paper to use solving programs developed by "Engineering Equation Solver" Software.

Using this software enables calculations on the one hand by providing various parameters of several substances, and on the other hand it allows easy plotting of graphs with the variation of quantities of interest.

2. Materials and Methods

From the existing types of conventional heat exchangers, the intermediate fluid one is characterized by the possibility of achieving many of the goals of an effective recovery of heat, less reducing operational safety. In addition, it greatly improves operational safety and maintenance by the fact that the mechanism of movement is inside each heat transfer element without any mechanical intervention from outside.

It is obvious that developing a heat recovery plant from secondary sources involves a certain amount of energy consumption consisting in: energy embedded in the materials that make up the facility, plus the energy used in its manufacturing operations technology. Thus, in considering the construction of a heat recovery system it is

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likely necessary to introduce energy indicators.

From the energy performance indices of heat recovery, we selected as most important: exergetic efficiency, the number of transfer units and efficiency.

Exergetic efficiency of a heat recovery is defined as the ratio of exergy variation of fluid flow cold ($\Delta\dot{E}_2$) and warm fluid ($\Delta\dot{E}_1$):

$$\eta_{ex} = \frac{\Delta\dot{E}_2}{\Delta\dot{E}_1} = \frac{\dot{E}_{22} - \dot{E}_{21}}{\dot{E}_{11} - \dot{E}_{12}} = \frac{\dot{M}_2(e_{22} - e_{21})}{\dot{M}_1(e_{11} - e_{12})} = 1 - \frac{\Delta\dot{E}_p}{\Delta\dot{E}_1} \qquad (1)$$

the meanings of the symbols are:

η_{ex} – exergetic efficiency of heat recovery;

$\dot{E}_{11}$, $\dot{E}_{12}$, $\dot{E}_{21}$, $\dot{E}_{22}$ – thermal exergy flows of agents into and out of the device [W];

e_{11}, e_{12}, e_{21}, e_{22} – specific exergy of the heat at the entry and exit of the machine [J / kg];

$\Delta\dot{E}_p$ – exergy flow heat lost by the recovery heat device [W].

Specific exergy of a fluid at the pressure "p" and temperature "t" is calculated using the formula:

$$e = (i - i_0) - T_0(s - s_0)\,[\text{J/Kg}] \qquad (2)$$

the meaning of the symbols is as follows:

i – fluid specific enthalpy [J / kg];

s – fluid specific entropy [J/Kg.K];

T_0 – ambient reference temperature [K];

i_0 – specific enthalpy of the fluid at temperature T_0;

s_0 – specific entropy of the fluid at temperature T_0;

For some fluids, including water, in the particular case that allowed ambient temperature is $T_0 = 273$ [K] resulting $i_0 = 0$, $s_0 = 0$.

In this case expression (2) becomes:

$$e = i - T_0 \cdot s\ [\text{J/Kg}]. \qquad (3)$$

Flow of exergy lost by a heat recovery is:

$$\Delta\dot{E}_p = \Delta\dot{E}_{sch} + \Delta\dot{E}_{\Delta p} + \Delta\dot{E}_{med}\ [\text{W}](4)$$

the physical parameters that appear are:

$\Delta\dot{E}_{sch}$ – exergy losses due to irreversibility of heat exchange at finite temperature difference [W];

$\Delta\dot{E}_{\Delta p}$ – exergy loss corresponding to pressure loss inside the recovery of heat device [W];

$\Delta\dot{E}_{med}$ – exergy loss due to heat loss in the environment of heat recovery device [W].

These exergy losses is calculated by relations:

$$\Delta\dot{E}_{sch} = \frac{T_0 \cdot \Delta t_{med}}{T_{m1} \cdot T_{m2}} \cdot \dot{Q}\ [\text{W}] \qquad (5)$$

$$\Delta\dot{E}_{\Delta P} = \Delta\dot{E}_{\Delta P1} + \Delta\dot{E}_{\Delta P2} = \frac{T_0}{T_{m1}} N_1 + \frac{T_0}{T_{m2}} N_2\ [\text{W}] \qquad (6)$$

$$\Delta E_{med} = \dot{Q}_P\left(1 - \frac{T_0}{T_{m1}}\right)\ [\text{W}], \qquad (7)$$

the meanings of the symbols are as follows:

T_0 – ambient reference temperature [K];

Tm1, Tm2 – average temperatures of thermal agents [K];

Δ_{tmed} – average temperature difference of thermal agents [K];

$\dot{Q}$ – heat load/charge of the recovery heat device [W];

N_1, N_2 – pumping power of the thermal agents inside the heat recovery device [W];

$\dot{Q}_P$ – heat flux lost in the environment [W].

The chart of calculation is as follows:

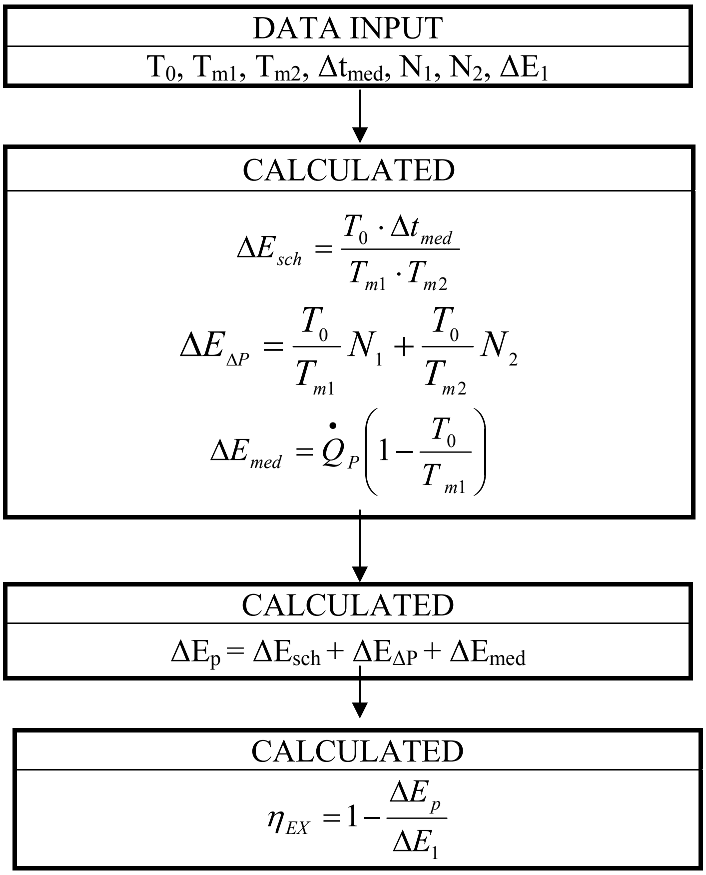


Fig. 1. *The chart for calculating the exergetic efficiency.*

Number of heat transfer units is defined as the product of overall heat transfer coefficient and heat transfer area relative to thermal heat capacity as follows:

$$NTU_1 = \frac{K \cdot S_1}{C_1}; \qquad (8)$$

$$NTU_2 = \frac{K \cdot S_2}{C_2}. \qquad (9)$$

Relations (8) and (9) can also write:

$$C_1 \cdot NTU_1 = KS_1 \rightarrow \dot{M}_1 \cdot c_{p1} \cdot NTU_1 = KS_1 \quad (10)$$

$$C_2 \cdot NTU_2 = KS_2 \rightarrow \dot{M}_2 \cdot c_{p2} \cdot NTU_2 = KS_2 \quad (11)$$

but:

$$\dot{M}_1 \cdot c_{p1} = \frac{\dot{Q}}{\Delta t_1} \;\&\; K \cdot S_1 = \frac{\dot{Q}}{\Delta t_{med}} \qquad (12)$$

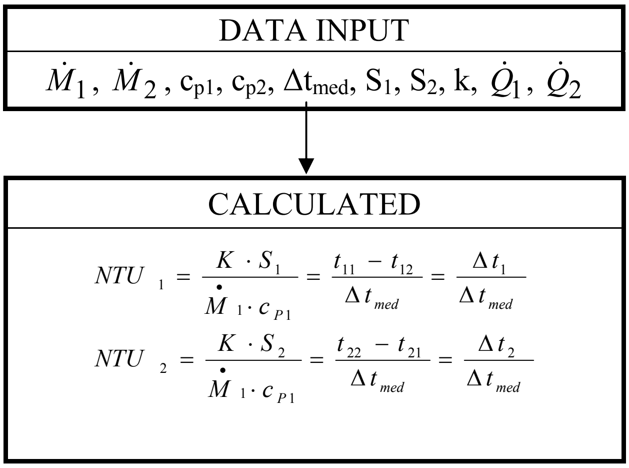
$$\dot{M}_2 \cdot c_{p2} = \frac{\dot{Q}}{\Delta t_2} \;\&\; K \cdot S_2 = \frac{\dot{Q}}{\Delta t_{med}} \qquad (13)$$

Substituting relations (12) and (13) in (10) and (11) we get:

$$\frac{\dot{Q}}{\Delta t_1} \cdot NTU_1 = \frac{\dot{Q}}{\Delta t_{med}} \rightarrow NTU_1 = \frac{\Delta t_1}{\Delta t_{med}} \qquad (14)$$

$$\frac{\dot{Q}}{\Delta t_2} \cdot NTU_2 = \frac{\dot{Q}}{\Delta t_{med}} \rightarrow NTU_2 = \frac{\Delta t_2}{\Delta t_{med}} \qquad (15)$$

The chart of calculation is as follows:



DATA INPUT

$\dot{M}_1$, $\dot{M}_2$, c_{p1}, c_{p2}, Δt_{med}, S_1, S_2, k, $\dot{Q}_1$, $\dot{Q}_2$

CALCULATED

$$NTU_1 = \frac{K \cdot S_1}{\dot{M}_1 \cdot c_{P1}} = \frac{t_{11} - t_{12}}{\Delta t_{med}} = \frac{\Delta t_1}{\Delta t_{med}}$$

$$NTU_2 = \frac{K \cdot S_2}{\dot{M}_1 \cdot c_{P1}} = \frac{t_{22} - t_{21}}{\Delta t_{med}} = \frac{\Delta t_2}{\Delta t_{med}}$$

Fig. 2. *The chart for calculating the number of transfer units*

Heat recovery device efficiency is defined as the ratio between the heat transfer and maximum flow that could be transfered in case of counter flow and if heat transfer surface would be infinite.

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{max}} = \frac{C_2(t_{22} - t_{21})}{C_{min}(t_{11} - t_{21})} = \frac{C_2 \cdot \Delta t_2}{C_{min} \cdot \Delta t_{max}} \qquad (16)$$

or:

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{max}} = \frac{\dot{C}_1(t_{11} - t_{12})}{\dot{C}_{min}(t_{11} - t_{21})} = \frac{\dot{C}_1 \cdot \Delta t_1}{\dot{C}_{min} \cdot \Delta t_{max}} \qquad (17)$$

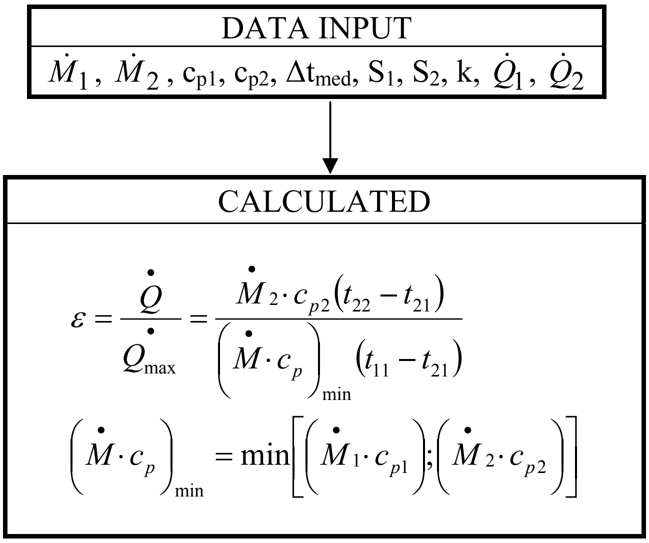
the meaning of the symbols is as follows:

ε – efficiency of the heat recovery device;

$\dot{C}_1$, $\dot{C}_2$ – flow of thermal capacity of primary or secondary thermal agents.

$$\dot{C}_1 = \dot{M}_1 \cdot c_{p1}; \dot{C}_2 = \dot{M}_2 \cdot c_{p2} \qquad (18)$$

The chart of calculation is as follows:



$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{\max}} = \frac{\dot{M}_2 \cdot c_{p2}\left(t_{22}-t_{21}\right)}{\left(\dot{M}\cdot c_p\right)_{\min}\left(t_{11}-t_{21}\right)}$$

$$\left(\dot{M}\cdot c_p\right)_{\min} = \min\left[\left(\dot{M}_1\cdot c_{p1}\right);\left(\dot{M}_2\cdot c_{p2}\right)\right]$$

Fig. 3. *The chart for calculating the efficiency*

From the technical and economic performance indicators of heat recovery, we selected as most important: quality energy index and economic indicators of quality.

Comparing different constructive solutions to the same thermal load ($\dot{Q}$) and same power (*N*) consumed for heating by circulating device can be done with relations of the form:

$$\frac{\dot{Q}}{G\cdot\Delta t_{med}} = f_1\left(\frac{\dot{Q}}{N\cdot\Delta t_{med}}\right) \qquad (19)$$

$$\frac{\dot{Q}}{V\cdot\Delta t_{med}} = f_2\left(\frac{\dot{Q}}{N\cdot\Delta t_{med}}\right) \qquad (20)$$

the meanings of the symbols are as follows:

G - unit weight [kg];

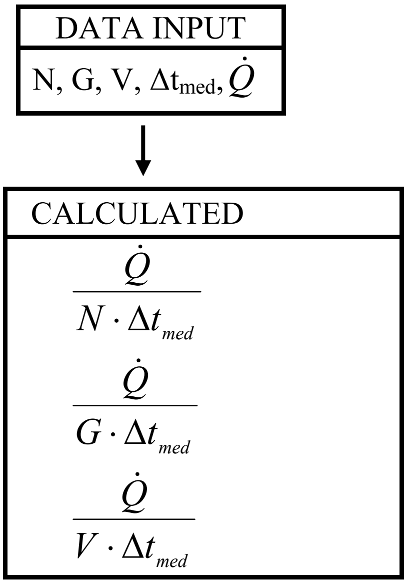
V - unit volume [m3];

Δ_{tmed} - average temperature difference between the thermal agents [° C];

$\frac{\dot{Q}}{N\cdot\Delta t_{med}}$ - Power quality index. This is an independent variable that expresses the heat flux transmitted at a mean temperature difference of 1K for 1kW power consumption for the circulating device.

$\frac{\dot{Q}}{G\cdot\Delta t_{med}}$; $\frac{\dot{Q}}{V\cdot\Delta t_{med}}$ - Economic indicators of quality. They cite the heat flux transferred to a mean difference of temperature of 1 [^{o}C] for a volume or mass unit of the heat recovery device.

Flowchart of calculation is as follows:



$$\frac{\dot{Q}}{N\cdot\Delta t_{med}}$$

$$\frac{\dot{Q}}{G\cdot\Delta t_{med}}$$

$$\frac{\dot{Q}}{V\cdot\Delta t_{med}}$$

3. Results and Discussions

Computer programs presented in this paper were originally employed on a stand in experimental investigations on heat recovery heat pipe made of copper and as a working fluid: water.

The results were subsequently verified by a heat recovery device made from materials used in building industry, which showed the validity of experimental results bench.

4. Conclusions

In the practice of heat recovery from secondary energy sources provided by various technological facilities are important on the one hand, the necessity to estimate recovery plant investment in question, and on the other hand, comparing different versions of a constructive potential recovery facilities in order to choose optimal solution over investment. Such analyzes require, in many cases, the consumption of significant resources of time, which makes use of an automatic calculation program feasible in practice.

The calculus routine presented in this paper were originally employed on a stand for experimental investigations on a heat pipe heat recovery system with copper pipes and water as intermediate fluid. The results were subsequently verified on a heat recovery system from the building materials industry. It was thus proved the validity of the experimental results obtained on the bench.

In general, heat recovery from secondary energy sources aimes to achieve at least two major objectives: energy material savings by reducing energy costs as heat and protect the environment by reducing emissions released into the atmosphere from burning conventional fuels.

Heat recovery from a secondary source of energy is generally appropriate if it is economically profitable, in case if recovery plant investment pays off by reducing energy costs in the form of heat. Among other technical and economic indicators, performance indicators of heat recovery are tools for assessing the effectiveness of different variants possible to determine optimal recovery solution.

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