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ENERGETIC AND EXERGETIC RESEARCH OF HEAT EXCHANGERS LIKE RADIATORS FOR MOTOR VEHICLES

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Abstract: *The constructive unit pipe-fin, which is found in any radiator for motor vehicles, can be considered the basic unit from the radiator assembly, and different variants can be obtained by different coupling in accordance with the circulation of both heat carriers. We resort to an exergetic analyze of the process, that offers a realistic view on phenomena, creating the possibility to localize the sources of loses. The work attempts to calculate the heat flow rate, the output of heat carriers' temperatures both, the thermal efficiency and the exergetic efficiency for two variants of radiators composed by "n" units and having different variants of connections: parallel or alternate tube disposition. In the case of the parallel disposition of tubes, on considers a parallel coupling from the water circulation and series coupling from the air circulation, but if pipes are alternate ranged, the coupling is parallel from the water circulation and parallel-series from the air circulation.*
Keywords (TNR 9 pt Bold): *heat transfer, heat exchangers, radiators, thermal efficiency, exergetic efficiency.*

1. INTRODUCTION

Because the heat transfer phenomena in heat exchangers are very complex, depending of many factors that are influenced reciprocally, it is difficult to obtain new and performance heat exchangers. This construction can be a basic unit to obtain other heat exchangers having same performances by series, parallel or mix coupling units.
The construction tube-fin that is included by all radiators for automotive can be considered a basic unit from an assembly composed by units coupled in various variants obtained by its disposing in conformity with both thermal carriers circulation (water and air). The work pursues to determinate heat flow rates, output temperatures of heat carriers, thermal efficiency and exergetic efficiency for two variants of radiators for automotive engines, having in line or staggered tube arrangement.

2. BASIC RELATIONS FOR CALCULUS

The thermal efficiency is defined by the subsequent equalities[1]:

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{\max}} = \frac{C_1 \cdot (T_{1i} - T_{1e})}{C_{\min} \cdot (T_{1i} - T_{2i})} = \frac{C_2 \cdot (T_{2e} - T_{2i})}{C_{\min} \cdot (T_{1i} - T_{2i})} = \frac{T_{2e} - T_{2i}}{T_{1i} + T_{2i}}, \tag{1}$$

in which with $\dot{C} = \dot{m} \cdot c$ is noted the heat capacity flow rate (where $\dot{m}$ is the mass flow rate and c - the specific heat), $\dot{Q}$ - the heat flux, T - the temperature and indexes are: for the primary and secondary fluid - 1, respectively 2, - the input and output section *i*, respectively *e*.
For a cross flow heat exchanger in which both fluids circulate unmixed (figure 1) are known relations for the thermal efficiency, heat flow rate and output temperatures of both fluids [2]:

$$\varepsilon = 1 - \exp \frac{\exp\left[-\frac{kS}{\dot{C}_2} \cdot \frac{\dot{C}_2}{\dot{C}_1} \cdot \left(\frac{kS}{\dot{C}_2}\right)^{-0.22}\right] - 1}{\frac{\dot{C}_2}{\dot{C}_1} \cdot \left(\frac{kS}{\dot{C}_2}\right)^{-0.22}}; \tag{2}$$

$$\dot{Q} = \dot{C}_1(T_{1i} - T_{1e}) = \dot{C}_2(T_{2e} - T_{2i}) = \varepsilon \cdot \dot{Q}_{\max} = \varepsilon \cdot \dot{C}_{\min}(T_{1i} - T_{2i}) = \varepsilon \cdot \dot{C}_2 \cdot (T_{1i} - T_{2i}); \tag{3}$$

$$T_{1e} = \beta \cdot (T_{1i} - T_{2i}) + T_{2i}; \tag{4}$$

$$T_{2e} = T_{2i} \cdot (1 - \varepsilon) + \varepsilon \cdot T_{1i}, \tag{5}$$

in which C^* is the ratio of thermal capacities:

$$C^* = \frac{\dot{C}_2}{\dot{C}_1} \tag{6}$$

and:

$$\beta = 1 - \varepsilon C^*. \tag{7}$$

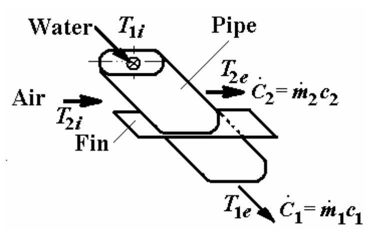

Figure 1: Cross-flow heat exchanger unit, both fluids unmixed

2. THE PARALLEL DISTRIBUTION

Figure 2 presents the parallel distribution of units in an automotive radiator.

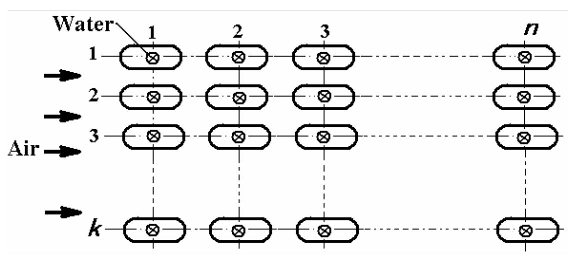

Figure 2: Parallel distribution of units

For a group of units composed by n units traversed in parallel by water and series by air it can write the subsequent relations for the heat flow rate of the n-th unit and output temperatures from this unit:

$$\dot{Q}_{np} = (1 - \varepsilon)^{n-1} \cdot \dot{Q}_1; \tag{8}$$

$$T_{1ep}^{(n)} = \beta \cdot (1-\varepsilon)^{n-1} \cdot (T_{1i} - T_{2i}) + \varepsilon \cdot (1-\varepsilon)^{n-2}(T_{1i} - T_{2i}) + \ldots + \varepsilon \cdot (T_{1i} - T_{2i}) + T_{2i}; \tag{9}$$

$$T_{2ep}^{(n)} = \varepsilon \cdot (1-\varepsilon)^{n-1} \cdot (T_{1i} - T_{2i}) + \varepsilon \cdot (1-\varepsilon)^{n-2}(T_{1i} - T_{2i}) + \ldots + \varepsilon \cdot (T_{1i} - T_{2i}) + T_{2i}, \tag{10}$$

in which $\dot{Q}_1$ represents the heat flux of a single unit. The overall heat flux for a single group is:

$$\dot{Q}_p^1 = \dot{Q}_1 + Q_{2p} + \ldots + \dot{Q}_{np} = \dot{Q}_1 + \dot{Q}_1(1-\varepsilon) + \ldots + \dot{Q}_1(1-\varepsilon)^{n-1} = \frac{1}{\varepsilon}\left[1 - (1-\varepsilon)^n\right] \cdot \dot{Q}_1. \tag{11}$$

For all k groups of units parallel traversed by water and air it results:

$$Q_p = \frac{k}{\varepsilon} \cdot \left[1 - (1-\varepsilon)^n\right] \cdot \dot{Q}_1; \tag{12}$$

$$T_{1ep} = (\beta - 1) \cdot (1-\varepsilon)^{n-1} \cdot (T_{1i} - T_{2i}) + T_{1i}; \tag{13}$$

$$T_{2ep} = T_{1i} - (1-\varepsilon)^n \cdot (T_{1i} - T_{2i}). \tag{14}$$

It results the overall thermal efficiency:

$$\varepsilon_{ps} = \frac{T_{2ep} - T_{2i}}{T_{1i} - T_{2i}} = \frac{T_{1i} - (1-\varepsilon)^n (T_{1i} - T_{2i}) - T_{2i}}{T_{1i} - T_{2i}} = 1 - (1-\varepsilon)^n \, . \tag{15}$$

The hot and respectively cold fluid entropy variation and mean temperature are:

$$\Delta\dot{S}_{1p} = \dot{m}_1 c_1 \ln\frac{T_{1i}}{T_{1ep}} = \dot{m}_1 c_1 \ln\frac{T_{1i}}{(\beta-1)(1-\varepsilon)^{n-1}(T_{1i} - T_{2i}) + T_{1i}} = -m_1 c_1 \ln\frac{\delta}{\delta + (\beta-1)(\delta-1)(1-\varepsilon)^{n-1}} \, ; \tag{16}$$

$$T_{m\dot{Q}1p} = \frac{\dot{Q}_p^1}{\Delta\dot{S}_{1p}} = \frac{\left[1-(1-\varepsilon)^n\right](1-\beta)(\delta-1)}{\varepsilon \cdot \ln\dfrac{\delta}{\delta + (\beta-1)(\delta-1)(1-\varepsilon)^{n-1}}} \cdot T_{2i} \, ; \tag{17}$$

$$\Delta\dot{S}_{2p} = \dot{C}_2 \ln\frac{T_{2ep}}{T_{2i}} = \dot{C}_2 \cdot \ln\frac{T_{1i} - (T_{1i} - T_{2i})(1-\varepsilon)^n}{T_{2i}} = \dot{C}_2 \cdot \ln\left[\delta - (\delta-1)(1-\varepsilon)^n\right]; \tag{18}$$

$$T_{m\dot{Q}2p} = \frac{(\delta-1)\left[1-(1-\varepsilon)^n\right]}{\ln\left[\delta - (\delta-1)(1-\varepsilon)^n\right]} \cdot T_{2i} \, , \tag{19}$$

in which:

$$\delta = T_{1i}/T_{2i} \, , \tag{20}$$

in order to realize a parametric analysis.
The exergetic efficiency corresponding to the heat transfer at a finite temperature difference can result from relation [3], [4]:

$$\eta_{ex.p} = 1 - \frac{\dot{E}_{Q2p}}{\dot{E}_{Q1p}} = \frac{\dfrac{T_{m\dot{Q}1p}}{T_{m\dot{Q}2p}} - 1}{\dfrac{T_{m\dot{Q}1p}}{T_{2i}} - 1} = \frac{a_p - b_p}{b_p \cdot (a_p - 1)} \, , \tag{21}$$

in which $\dot{E}_{Q1}$, $\dot{E}_{Q2}$ represent the exergy flux corresponding to the heat flux transferred by the primary, respectively the secondary fluid and:

$$a_p = \frac{T_{m\dot{Q}1p}}{T_{2i}} = \frac{[1-(1-\varepsilon)^n] \cdot (1-\beta) \cdot (\delta-1)}{\varepsilon \cdot \ln\dfrac{\delta}{\delta + (\beta-1)(\delta-1)(1-\varepsilon)^{n-1}}} \, ; \tag{22}$$

$$b_p = \frac{T_{m\dot{Q}2p}}{T_{2i}} = \frac{(\delta-1)\left[1-(1-\varepsilon)^n\right]}{\ln\left[\delta - (\delta-1)(1-\varepsilon)^n\right]} \, . \tag{23}$$

3. THE STAGGERED DISTRIBUTION

Figure 3 presents the staggered distribution of units in an automotive radiator.

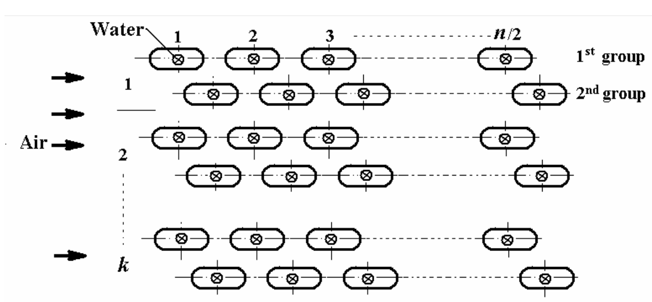

Figure 3: Staggered distribution of units

The study of this variant can be accomplished by considering two groups composed by $n/2$ units parallel coupled for water circulation and series coupled for air circulation. It results for the 1st or the 2nd group:

$$\dot{Q}_s^{(n/2)} = \frac{1}{\varepsilon}\left[1-(1-\varepsilon)^{\frac{n}{2}}\right]\cdot \dot{Q}_1\,; \tag{24}$$

$$T_{1es}^{(n/2)} = (\beta-1)(1-\varepsilon)^{\frac{n}{2}-1}\left(T_{1i}-T_{2i}\right)+T_{1i}\,; \tag{25}$$

$$T_{2es}^{(n/2)} = T_{1i}-(1-\varepsilon)^{\frac{n}{2}}\left(T_{1i}-T_{2i}\right). \tag{26}$$

If it is considered both groups parallel coupled for water and air circulation there are obtained relations for heat flux and thermal efficiency in the case of this staggered disposition:

$$\dot{Q}_s^{(n)} = 2\cdot \dot{Q}_s^{(n/2)} = \frac{2}{\varepsilon}\cdot\left[1-(1-\varepsilon)^{\frac{n}{2}}\right]\cdot \dot{Q}_1\,; \tag{27}$$

$$\varepsilon_s = \frac{T_{2es}^{(n/2)}-T_{2i}}{T_{1i}-T_{2i}} = \frac{T_{1i}-(1-\varepsilon)^{\frac{n}{2}}\left(T_{1i}-T_{2i}\right)}{T_{1i}-T_{2i}} = 1-(1-\varepsilon)^{\frac{n}{2}}. \tag{28}$$

For all k groups composed by all n units parallel traversed by water and air it results:

$$\dot{Q}_s = k\cdot \dot{Q}_s^{(n)} = \frac{k}{\varepsilon}\cdot\left[1-(1-\varepsilon)^{\frac{n}{2}}\right]\cdot \dot{Q}_1\,; \tag{29}$$

The hot and respectively cold fluid entropy variation and mean temperature are:

$$\Delta\dot{S}_{1s}^{(n)} = \dot{C}_1\cdot\ln\frac{T_{1i}}{T_{1es}^{n/2}} = \dot{C}_1\cdot\ln\frac{T_{1i}}{(\beta-1)(1-\varepsilon)^{\frac{n}{2}-1}\left(T_{1i}-T_{2i}\right)+T_{1i}} = \dot{C}_1\cdot\ln\frac{\delta}{\delta+(\delta-1)(\beta-1)(1-\varepsilon)^{\frac{n}{2}-1}}\,; \tag{30}$$

$$T_{m\dot{Q}1s} = \frac{2\cdot(1-\beta)(\delta-1)\left[1-(1-\varepsilon)^{\frac{n}{2}}\right]}{\varepsilon\cdot\ln\dfrac{\delta}{\delta+(\delta-1)(\beta-1)(1-\varepsilon)^{\frac{n}{2}-1}}}\cdot T_{2i}\,; \tag{31}$$

$$\Delta\dot{S}_{2s}^{(n)} = 2\cdot\dot{C}_2\cdot\ln\frac{T_{2es}^{(n/2)}}{T_{2i}} 2\cdot\dot{C}_2\cdot\ln\frac{T_{1i}-(1-\varepsilon)^{\frac{n}{2}}\left(T_{1i}-T_{2i}\right)}{T_{2i}} = 2\cdot\dot{C}_2\cdot\ln\left[\delta-(1-\varepsilon)^{\frac{n}{2}}\cdot(\delta-1)\right]; \tag{32}$$

$$T_{m\dot{Q}2s} = \frac{Q_s^{(n)}}{\Delta\dot{S}_{2s}^{n}} = \frac{(\delta-1)\left[1-(1-\varepsilon)^{\frac{n}{2}}\right]}{\ln\left[\delta-(1-\varepsilon)^{\frac{n}{2}}(\delta-1)\right]}\cdot T_{2i}\,. \tag{33}$$

The exergetic efficiency can result from relation:

$$\eta_{ex.p} = 1-\frac{\dot{E}_{Q2s}}{\dot{E}_{Q1s}} = \frac{\dfrac{T_{m\dot{Q}1s}}{T_{m\dot{Q}2s}}-1}{\dfrac{T_{m\dot{Q}1s}}{T_{2i}}-1} = \frac{a_s-b_s}{b_s\cdot(a_s-1)}\,, \tag{34}$$

in which:

$$a_s = \frac{T_{m\dot{Q}1s}}{T_{2i}} = \frac{2(1-\beta)(\delta-1)\left[1-(1-\varepsilon)^{\frac{n}{2}}\right]}{\varepsilon\cdot\ln\dfrac{\delta}{\delta+(\delta-1)(\beta-1)(1-\varepsilon)^{\frac{n}{2}-1}}}\,; \tag{35}$$

$$b_s = \frac{T_{m\dot{Q}2s}}{T_{2i}} = \frac{(\delta-1)\cdot\left[1-(1-\varepsilon)^{\frac{n}{2}}\right]}{\varepsilon\cdot\ln\left[\delta-(1-\varepsilon)^{\frac{n}{2}}\cdot(\delta-1)\right]}\,. \tag{36}$$

4. COMPARISONS

In order to compare both variants of pipe arrangement in an automotive radiator were plotted the calculus results starting from the experiments carried out for a real radiator: water mass flow rate, $\dot{m}_1 = 1\,\text{kg/s}$; air mass flow rate, $\dot{m}_2 = 2\,\text{kg/s}$; water specific heat, $c_1 = 4187\,\text{J/kg}\cdot\text{K}$; air specific heat, $c_2 = 1004.65\,\text{J/kg}\cdot\text{K}$; overall heat transfer coefficient $k = 146\,\text{W/m}^2\text{K}$; heat transfer surface, $S = 9.2\,\text{m}^2$.

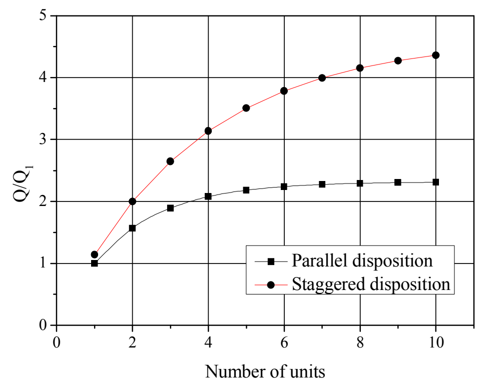

Figure 4: The ratio of the heat flux of the assembly to the heat flux of a single unit as a function of number of units

There are considered reasonable values for both fluids input temperatures: $T_{1i} = 363.15\,\text{K}$ and $T_{2i} = 293.15\,\text{K}$.

For the parametric analysis, computing relations (2), (7) and (20) it results: $\varepsilon = 0.4310141$; $\beta = 0.7931606$; $\delta = 1.2387856$.

In figure 4 is plotted the ratio $\dot{Q}/\dot{Q}_1$ as a function of number of units, *n*. It comes out that this ratio is bigger for the staggered disposition. This conclusion is known in the literature, resulted from many experiences. Otherwise the heat flow rate $\dot{Q}$ is the most important parameter in the radiator operating.

In figures 5 and 6 are plotted the output temperatures of both fluids as a function of number of units *n*, for both arrangements of pipes (units). It comes out that both temperatures are bigger in the case of the parallel arrangement.

From figures 2 and 3 it can observe that the number of units crossed by air in a single row is double for the parallel disposition and thus the air temperature is bigger. On the other hand, water flows in parallel into pipes (units) and so it is more cooled in the staggered arrangement.

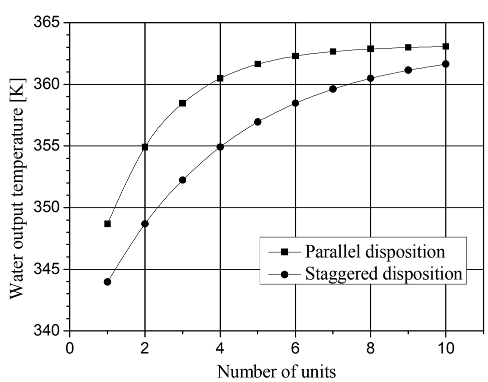

Figure 5: The output water temperature as a function of number of units

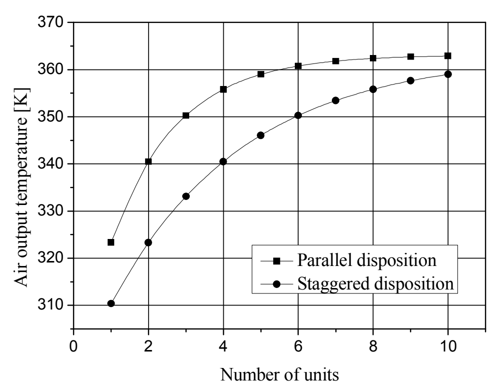

Figure 6: The output air temperature as a function of number of units

Figure 7 shows the thermal efficiency as a function of number of units. It results a fastly increasing of the thermal efficiency with the number of units in the case of the parallel disposition, reaching values close the unity. The curve for the staggered disposition starts from a slow value but has an approximately constant increasing. Both curves can approach after more 10 rows.

In figure 8 are plotted curves of the exergetic efficiency function of the number of units. It comes out that the exergetic efficiency is bigger for the staggered disposition of units. Given the thermal efficiency the ratio is inversed.

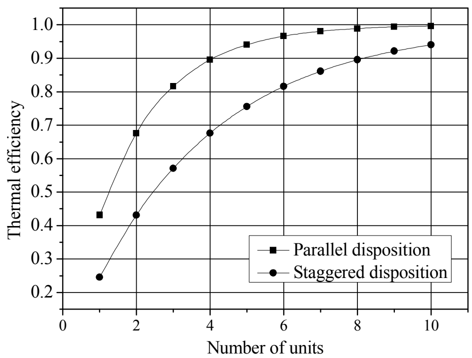

Figure 7: Thermal efficiency as a function of number of units

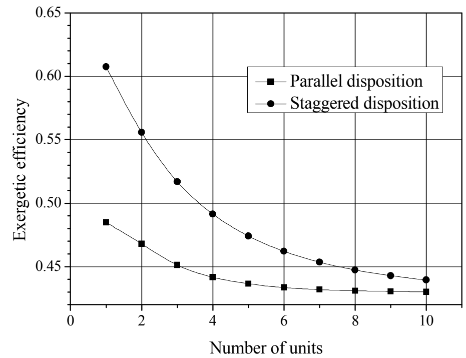

Figure 8: Exergetic efficiency as a function of number of units

5. CONCLUSION

The work attempts to calculate the heat flow rate, the output of heat carriers' temperatures both, the thermal efficiency and the exergetic efficiency for two variants of radiators composed by "n" units and having different variants of connections: parallel or alternate tube disposition.
The main goal of the radiator for automotive is the best cooling of the primary fluid (water). It comes out that the staggered disposition is good because the heat flow rate is bigger and the water output temperature value is lower. But the thermal efficiency, considered in the classic theory the main parameter that sort out heat exchangers is best for the parallel arrangement.
From this reason, the work determines the exergetic efficiency corresponding to the heat transfer at a finite temperature difference. It results that the staggered arrangement is good, so the final conclusion is that this arrangement is the best.

REFERENCES

[1] Badea A. Necula H., Stan M., Ionescu L., Blaga P., Darie G. Echipamente si instalatii termice. Editura Tehnica, Bucuresti, 2003.
[2] Kreith F. Handbook of thermal engineering. CRC Press, Boca Raton, Florida, USA, 2000.
[3] Serbanoiu N., Muresan M., Ungueranu V.B., Mihalcea M. Modular heat exchangers. Schimbatoare de caldura formate din module. Editura Universitatii Transilvania, Brasov, 2007.
[4] Serbanoiu N., Muresan M., Ungueranu V.B. Energetically and exergetically aspects on the heat exchangers composed by units. Proceedings of the 3th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics, HEFAT 2004, Cape Town, South Africa, 21-24 April 2004.