EXPERIMENTAL RESEARCHES ON THE THERMAL TRANSFER OF FLUIDS FLOWING THROUGH ALCO 18 OIL COOLER

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Abstract: The paper presents theoretical and experimental researches on ALCO 18 oil cooler. The oil cooler equips the ALCO R 251 FLO engine used for cogeneration. The theoretical results are obtained with MATLAB software. Based on both experimental and theoretical results the criteria equation \( Nu = 0.0226 \cdot Re^{0.546} \cdot Pr^{0.33} \) was obtained. In addition, variations of heat exchange global coefficient, convection coefficient, \( Nu = f(Re) \) and \( j = f(Re) \) are presented in the paper.

As a conclusion of this comparative study it can be observed that the differences between theoretical estimations and experimental results are small, showing that this application can be successfully use in cogeneration systems. Key words: oil cooler, mass flow, thermal flow, capacity flux.

1. RECIROCATING ENGINES IN COGENERATION

Cogeneration (also combined heat and power, CHP) is the use of a heat engine or a power station to simultaneously generate both electricity and useful heat. Conventional power plants emit the heat created as a byproduct of electricity generation into the environment through cooling towers, as flue gas, or by other means. CHP or a bottoming cycle captures the byproduct heat from domestic or industrial heating purposes, either very close to the plant, or for distribution through pipes to heat the local housing. Cogeneration assumes a wide scale of technologies for applications in different economical activities areas. The efficiencies can come to 80% or even higher by using cogeneration systems.

Reciprocating engines are used in lower or medium power cogeneration units. The small or big engines dimensions are often depending on the used fuel. One of the major advantages of reciprocating engines is the high electrical efficiency \(^6\).

In thermal engines an important part of energy losses because of processes irreversibility. There are cases when losses can be used in cogeneration installations and the option for such an installation is determined by economical and ecological factors. Different engines (gas engines, diesel engines) can be used in these installations, the ratio between thermal energy and consumed energy depends on components that are utilized.

Usually cogeneration plants with internal combustion engines are recommended for low ratios between the provided heat flow and electrical power.

In diesel engines cogeneration plants above 42% from primary used energy is converted into electrical energy (58% from input energy can be find both as heat from the cooling circuits and dissipated with exhausted gasses in the atmosphere) \(^5\).

For such a diesel engine cogeneration plant there are three mediums that can be cooled which are presented in Fig. 1 \(^8\):
- The engine overcharged air,
- The lubricated oil,
- The cooling water.
2. THE ALCO 18 OIL-WATER COOLER

In the paper is presented the criteria equation determined in graphic form for the perpendicular on a staggered bank of tubes fluid flow for ALCO 18 oil-water cooler. Oil coolers for locomotive diesel engines are heat exchangers with jacket staggered bank of tubes. The tubes disposal is parallel. Inside the tubes the thermal agent is water flowing in two paths into the heat exchanger and outside the tubes is flowing the oil. The oil flowing is transversal over the staggered bank of tubes, in ten transversal passages (there are nine route plates)[3,4].

By taking into account that the specialty literature is very poor in thermal transfer criteria equations, for this heat exchanger type is almost impossible the thermal calculation concerning the overall heat transfer coefficient for certain working conditions. Therefore, the heat exchangers are tested on test stands. The ALCO 18 was tested onto a test stand which permitted performing certain working conditions. The installation is used to determine the thermal performances of the ALCO 18 cooler which equips the R 251 FLO diesel engine, presented in Fig. 2.

For R 251 FLO diesel engine is used an ALCO 18 oil cooler. This cooler scheme is presented in Fig. 3.

The test conditions for the oil cooler were:
- The water mass flow:
  \[ m_w = 10.4...20.8 \text{ kg/s}; \]
- The oil mass flow:
  \[ m_o = 4...18 \text{ kg/s}; \]
- The oil inlet temperature:
  \[ t_o = 78 \degree C...80 \degree C; \]
- The water inlet temperature:
  \[ t_w = 62 \degree C...70 \degree C; \]
- The oil flowing speed:
  \[ w_o = 0.3...1.8 \text{ m/s}; \]
- The water flowing speed:
  \[ w_w = 0.8...1.8 \text{ m/s}. \]

The water mass flow was modified as \( t_o, t_w \) and \( m_o \) were maintained constant. Than the oil mass flow was varied between the same limits, obtaining a big number of measurements.

Fig. 1. The three cooling mediums in a diesel engine cogeneration installation

Fig. 2. The diesel engine R251 FLO test stand
The thermal calculation was accomplished based on the data obtained as a result of the experimental researches. The experimental results refer to the overall heat transfer coefficient from the oil to the cooler wall related to the cooler external surface on the oil side. This calculation involves nine parameters as it follows [7]:

- $Q \left[ W \right]$ - the heat flow transmitted between oil and water;
- $K \left[ W/m^2K \right]$ – the overall heat transfer coefficient;
- $A \left[ m^2 \right]$ – the thermal transfer surface;
- $C_u, C_w \left[ W/K \right]$ - the total capacity flux;
- $t'_{u}, t'_w, t''_{u}, t''_w \left[^\circ C \right]$ – the two fluids inlet and outlet temperatures.

These parameters are connected by the following relations:

- The heat flow given by the oil:
  \[
  \dot{Q}_u = C_u \left( t'_{u} - t''_{u} \right)
  \] (1)
- The heat flow received by the water:
  \[
  \dot{Q}_w = C_w \left( t'_{w} - t''_{w} \right)
  \] (2)
- The heat flow transmitted through the heat surface:
  \[
  Q = \frac{\dot{Q}_u + \dot{Q}_w}{2} = k_u A \Delta t_m = C_u \Phi \left( t'_{u} - t''_{u} \right)
  \] (3)

For the thermal calculations of the oil cooler it is necessary to know six from the nine parameters. The other three parameters will result from the (1), (2), (3) relations.

- The cooler exploitation characteristic (real efficiency):
  \[
  \Phi = \frac{Q}{m_u \cdot c_u \cdot \left( t'_{u} - t''_{u} \right)} = \frac{t'_{u} - t''_{u}}{t'_u - t''_u}
  \] (4)
This function depends on non-dimensional measures:

$$
\mu = \frac{C_v}{C_w} = \frac{t_u - t_w}{t_u - t_w} \leq 1
$$  (5)

$$
\chi = \frac{k \cdot A}{C_v} = \frac{t_u - t_w}{\Delta t_m}
$$  (6)

For this cooler the mixed fluid is oil and the unmixed fluid is water. For calculation the criteria equation was used [2]:

$$
\chi = -\ln[1 + \mu \ln(1 - \mu \cdot \Phi)]
$$  (7)

The analytical expression of the criteria equation depends on the two fluids flowing mode through the cooler:

$$
\Phi = \Phi(\chi, \mu)
$$  (8)

The medium temperature difference $\Delta t_m$ can be calculated with the medium temperature difference for the counter flowing fluids $\Delta t_{mc}$:

$$
\Delta t_m = \varepsilon \cdot \Delta t_{mc}
$$  (9)

Where:

$$
\Delta t_{mc} = \frac{(t_u - t_u) - (t_w - t_w)}{\ln \frac{t_u - t_u}{t_w - t_w}}
$$  (10)

The $\varepsilon$ correction coefficient shows the heat exchange aggravation in the cooler in comparison with a counter flow heat exchanger that is the most favorable solution. This coefficient may be calculated as a ratio between the $\chi$ criteria for the fluids counter flow and $\chi$ criteria for the given flowing mode into the heat exchanger:

$$
\varepsilon = \frac{\Delta t_m}{\Delta t_{mc}} = \frac{\chi_c}{\chi} = f(\Phi, \mu)
$$  (11)

Similarity criteria used for heat exchangers are:
- The Reynolds number:

$$
Re = \frac{w \cdot l}{\nu}
$$  (12)

Where:

- $w$ [m/s] – the fluid flowing speed;
- $l$ [m] – the characteristic dimension (for pipes: hydraulic diameter $d_e$);
- $\nu$ [m$^2$/s] – the fluid kinematics viscosity.
- The Prandtl number:

$$
Pr = \frac{\nu \cdot \rho \cdot c}{\lambda}
$$  (13)

Where:

- $\rho$ [kg/m$^3$] – the density;
- $c$ [J/kg K] – the specific heat capacity;
- $\lambda$ [W/m K] – the thermal conductivity.
- The Nusselt number:

$$
Nu = \frac{\alpha \cdot l}{\lambda}
$$  (14)

Where:

- $\alpha$ [W/m$^2$K] – the heat transfer coefficient.
- The Stanton number:

$$
St = \frac{Nu}{Re \cdot Pr}
$$  (15)

- The Colborn number:

$$
\jmath = St \cdot Pr^\frac{1}{2} = \frac{Nu}{Re \cdot Pr^\frac{1}{2}}
$$  (16)

All the thermal proprieties involved in the similarity criteria are determined depending on the two fluids average temperatures (inlet/outlet).
The characteristic dimension for the above similarity criteria is the pipe internal diameter for the water flow, respective the hydraulic diameter for the oil flow.
The relation for the hydraulic diameter is [9]:

$$
d_h = \frac{4 \cdot S}{P} = \frac{D^2 - n \cdot d_e^2}{D_t + n \cdot d_e}
$$  (17)
Where:
\( D_i [m] \) – The jacket internal diameter;
\( d_e [m] \) – The pipe external diameter;
\( n \) – The number of pipes;
\( S [m^2] \) – The flowing surface area;
\( P [m] \) – The perimeter;

### 4. DETERMINATION OF THE CRITERIA EQUATION IN GRAPHIC FORM FOR THE FLUID FLOWING PERPENDICULAR ON THE OIL COOLER STAGGERED BANK OF TUBES

The diagram of the criteria equation:

\[ j = f(Re) \]  \hspace{1cm} (18)

which is presented in Fig. 4 allows a quick determination of the ALCO 18 cooler performances for a concrete given case. However, the diagram utilization presents some disadvantages:
- the values are not the real ones;
- requires a precise measurement system of the values on the diagram;
- doesn’t allow to use the numerical calculation in a program in order to study the variation of some parameters. In this case, the problem is to determine a criteria equation in the analytical shape that is often used in the specialty literature.

Based on the experimental results, for the oil cooler it will be determined a criteria equation as it follows:

\[ Mn = C \cdot Re^x \cdot Pr^y \]  \hspace{1cm} (19)

Based on the (18) relation and by expressing the Colborn number:

\[ j = C \cdot Re^x \]  \hspace{1cm} (20)

Results:

\[ \ln j = \ln C + x \ln Re \]  \hspace{1cm} (21)

For \( \ln j = a \), \( \ln C = y \) and \( \ln Re = b \), results the following relation:

\[ a = y + bx \]  \hspace{1cm} (22)

If for \( a \) and \( b \) are given values for two arbitrary points on the graphic, results a two equations system with two unknown values that leads to a \( j = f(Re) \) function. Thus, it can be obtained a large number of relations of the (19) type.

From the large number of resulted equations it will be chosen [1]:

\[ Nu = 0.0226 \cdot Re^{0.546} \cdot Pr^{0.33} \]  \hspace{1cm} (23)

Based on this equation it was graphically represented in Fig. 5 the function \( j_{cr} = f(Re) \).

![Fig. 4 Analytical versus experimental diagrams \( j = f(Re) \)](image)

![Fig. 5 Criteria versus experimental diagrams \( j_{cr} = f(Re) \)](image)

![Fig. 6. Analytical versus experimental diagrams \( Nu = \) (Re)](image)
5. CONCLUSIONS

The optimum values obtained as a result of experimental researches for oil and water masses flow are \( m_o = 15.939 \text{ kg/s} \) respective \( m_w = 20 \text{ kg/s} \). The optimum value mentioned before was for \( t_u = 80 \text{ °C} \) when efficiency is \( \Phi = 0.28 \). If both the oil temperature at cooler entrance and the heat exchanger efficiency are increasing, the cooler will have a good behavior also at \( t_u = 95 \text{ °C} \). By taking into account the fact that the oil viscosity decreases, both from thermal and fluid dynamic point of view, the pressure variation on heat exchanger on the oil side for the same value of mass flow will decrease.

It can be observed that the criteria function represented with (23) relation draws very much near to the graphic represented based on the experimental results. That means the criteria equation was correctly determined. This criteria equation:

\[
Nu = 0.0226 \cdot Re^{0.546} \cdot Pr^{0.33}
\]

is a generalization of the obtained results. From the figures above it can be observed that the flowing regime is laminar. The Reynolds number value is between 300 and 600. The representation of the diagrams points was made on a logarithmic scale, corresponding to the Re values on the horizontal axis.

Thus, experimental researches were correctly realized that means the determined values characterize the ALCO 18 oil cooler real operation. Theoretical represented values, obtained with MATLAB software, are between normal limits in comparison with experimental values, the average experimental uncertainty value being around 20 percent. This comparative study shows that the differences between the theoretical estimations and experimental results are small, meaning that this application can be successfully used in cogeneration systems.

6. REFERENCES


7. DATA ABOUT AUTHOR

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