METALLURGY AND FOUNDRY ENGINEERING – Vol. 37, 2011, No. 2

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SIMPLIFIED METHOD OF HEAT CALCULATIONS OF OIL-AIR HEAT EXCHANGERS

Notation:

α – convection heat-transfer coefficient, W/(m^2·K)
c – mean heat capacity, kJ/(m^3·K)
d – diameter, m
F – heating surface area, m^2
k – over-all heat-transfer coefficient, W/(m^2·K)
L – height of fin, m
λ – thermal conductivity, W/(m·K)
m – parameter of fin, m
M – mass rate of fluid flow, kg/s
p – pitch of fines, m
r – radius, m
s – thickness of fin, m
t – temperature, K
ρ – density, kg/m^3
μ – viscosity coefficient, kg/(m·s)
w – velocity, m/s
V – volumetric rate of fluid flow, m^3/s
Q – heat transfer rate, W
η – efficiency

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1. INTRODUCTION

New constructions of heat exchangers require research on the intensification of heat transfer realized by Mean Direct Action on the Flow or Surface Development methods [1, 4, 5]. Intensification of heat transfer in exchanger increases over-all heat transfer coefficient and efficiency, also reduces construction materials costs. For calculation of heat exchangers designs Mean Temperature Difference method and Heat Effectives one are used [6, 8]. The both methods are based on universal equal of energy balance. The aim this paper is new method of calculations oil-air exchangers made of cross-finned aluminium pipes.

2. UNIVERSAL EQUATIONS OF HEAT TRANSFER

Heat transfer rate of oil-air exchangers is described by equations (1, 2):

$$Q = V_a c_a \left(t_a'' - t_a' \right) \tag{1}$$

where:

V_a – volumetric rate of air flow,
c_a – mean heat capacity of air,
t_a' – inlet air temperature,
t_a'' – outlet air temperature.

$$Q = kF \left(\overline{t}_f - \overline{t}_a \right) \tag{2}$$

where:

k – over-all heat transfer coefficient,
F – heating surface area,
$\overline{t}_f$ – mean temperature of oil,
$\overline{t}_a$ – mean temperature of air.

Over-all heat transfer coefficient [1, 8] is:

$$k = \frac{1}{\dfrac{\varphi_o}{\alpha_f} + \dfrac{1}{\alpha_r}} \tag{3}$$

where:

α_f – convection heat transfer coefficient from oil to wall,
α_r – reduced heat transfer coefficient,
φ_o – finning ratio.

$$\varphi_o = \frac{F}{F_r} \tag{4}$$

where:

F – surface finned area,

F_r – surface area of smooth pipe.

Influence of efficiency on heat transfer describes reduced heat-transfer coefficient by equation:

$$\alpha_r = \alpha_o \left(\frac{F_m}{F_r} + \frac{F_{\dot{z}}}{F_r} \eta \right) \tag{5}$$

where:

α_o – convection heat-transfer coefficient of smooth element,

F_m – surface area between fins,

$F_{\dot{z}}$ – surface area of fins,

F_r – surface area of smooth pipe,

η – efficiency.

Figure 1 illustrates the cross-finned pipe with circular fins of constant thickness.

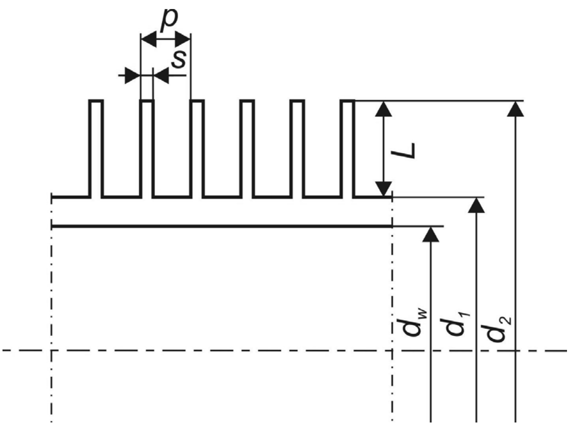

Fig. 1. *The cross-finned pipe: d_w – inner diameter of pipe, d_1 – outer diameter of pipe, d_2 – outer diameter of finned pipe, L – height of fin,* s *– thickness of fin, p – pitch of fines*

For diameters ratio of pipe $d_1/d_w < 2$ it is possible to calculate over-all heat-transfer coefficient as for plane wall [7], by equation (3).

3. RESEARCH OF ELEMENTS OF THE HEAT EXCHANGERS MADE OF CROSS-FINNED ALUMINIUM PIPES

The tested element of heat exchangers has the following geometric, flow, and temperature parameters:

- inner diameter of element $d_w = 0.025$ m,
- outer diameter of element $d_1 = 0.030$ m,
- outer diameter of finned element $d_2 = 0.052$ m,
- height of fin $L = 0.011$ m,
- thickness of fin $s = 0.00045$ m,
- pitch of fin $p = 0.00252$ m,
- inlet air temperature $t'_a = 18.3\ ^{o}C$,
- outlet air temperature $t''_a = 23.5\ ^{o}C$,
- inlet oil temperature $t'_f = 70.1\ ^{o}C$,
- outlet oil temperature $t''_f = 66.6\ ^{o}C$,
- mass rate of oil flow $M_f = 0.35$ kg/s,
- volumetric rate of air flow $V_a = 0.365\ m^3/s$,
- surface area of air flow $F_a = 0.00317\ m^2$,
- surface area of oil flow $F_f = 0.0112\ m^2$,
- lenght of element $l = 0.295$ m,
- simplex of diameters $d_1/d_2 = 1.2$,
- quantity of elements $n = 23$,
- heat surface area of exchanger $F = 1.15\ m^2$.

According to Schmidt [9] efficiency of circular fin is described by equation:

$$\eta = \frac{tgh\left(mL_c\varphi\right)}{mL_c\varphi} \tag{6}$$

where:

$$\varphi = 1 + 0.35\ln\left(1 + \frac{L_c}{r_1}\right) = 1 + 0.35\ln\left(1 + \frac{0.0114}{0.015}\right) = 1.198,$$

$$L_c = r_{2c} - r_1 = 0.0264 - 0.015 = 0.0114\ \text{m},$$

$$r_1 = \frac{d_1}{2} = \frac{0.030}{2} = 0.015\ \text{m},$$

$$r_2 = \frac{d_2}{2} = \frac{0.052}{2} = 0.026 \text{ m},$$

$$r_{2c} = \frac{d_2 + s}{2} = \frac{0.052 + 0.00045}{2} = 0.0264 \text{ m}.$$

Parameter of fin is:

$$m = \sqrt{\frac{2\alpha}{\lambda s}} = \sqrt{\frac{2 \cdot 45.4}{165 \cdot 0.00045}} = 34.96 \text{ m},$$

where:

convection of heat-transfer coefficient delivered to surface area of smooth pipe $\alpha_o = 45.4$ W/(m^2·K),
thermal conductivity of aluminium ë = 165 W/(m·K),
thickness of fin $s = 0.00045$ m,
$m \cdot L_c = 34.96 \cdot 0.0114 = 0.399 \text{ m}^2$,

$$\eta = \frac{tgh(34.96 \cdot 0.0114 \cdot 1.198)}{34.96 \cdot 0.0114 \cdot 1.198} = 0.97.$$

According to Brandt [9] efficiency of circular fin is described by equation:

$$\eta = \frac{2r_1}{2r_1 + L_c} \frac{tgh\, mL_c}{mL_c} \left[1 + \frac{tgh\, mL_c}{2mr_1} + 0.071882 \frac{(tgh\, mL_c)^{3.7482}}{(mr_1)^{1.481}} \right] \tag{7}$$

where:

$r_1 = 0.015 \text{ m}, L_c = 0.014 \text{ m}, m = 34.96 \text{ m}.$

$$\eta = \frac{2 \cdot 0.015}{2 \cdot 0.015 + 0.014} \frac{tgh\, 34.96 \cdot 0.014}{34.96 \cdot 0.014} \left[1 + \frac{tgh(34.96 \cdot 0.014)}{2 \cdot 34.96 \cdot 0.015} + \right.$$

$$\left. + 0.071882 \frac{(tgh\, 34.96 \cdot 0.015)^{3.7482}}{(34.96 \cdot 0.015)^{1.481}} \right] = 0.93.$$

Efficiency of circular fin is described [9] also by equation:

$$\eta = \frac{1}{1 + \frac{1}{3}(mL_c)^2 \sqrt{\frac{r_{2c}}{r_1}}} \tag{8}$$

where:

$mL_c = 0.399\ \mathrm{m}^2, r_{2c} = 0.0264\ \mathrm{m}, r_1 = 0.015\ \mathrm{m}.$

$$\eta = \frac{1}{1+\frac{1}{3}(0.399)^2\sqrt{\frac{0.0264}{0.015}}} = 0.93.$$

4. RESEARCH OF HEAT TRANSFER COEFFICIENTS

Heat transfer coefficient on oil side
Surface area of oil flow is:

$$F_f = 23\frac{\pi d_w{}^2}{4} = 23\frac{\pi \cdot 0.025^2}{4} = 0.0112\ \mathrm{m}^2.$$

Velocity of oil is:

$$w_f = \frac{M_f}{\rho F_f} = \frac{0.35}{864 \cdot 0.0112} = 0.036\ \mathrm{m/s},$$

where: density of oil $\rho_f = 864\ \mathrm{kg/m}^3$.

Reynolds number is:

$$\mathrm{Re} = \frac{w_f d_w \rho_f}{\mu} = \frac{0.036 \cdot 0.025 \cdot 864}{60.558 \cdot 10^{-4}} = 128.4,$$

where:

mean temperature of oil $\bar{t}_f = \frac{70.1 + 66.6}{2} = 68.4\ ^{\mathrm{o}}\mathrm{C}$,

dynamic viscosity coefficient of oil [10] $\mu = 60.558 \cdot 10^{-4}$ kg/(m·s).

According to Mikheyev [7] for laminar flow of oil heat transfer coefficient is described by similarity equation:

$$\mathrm{Nu} = 1.4\,\mathrm{Re}^{0.4}\,\mathrm{Pr}^{0.33}\left(\frac{d}{l}\right)^{0.4} \tag{9}$$

Prandtl number is:

$$\mathrm{Pr} = \frac{c_f\,\mu}{\lambda_f} = \frac{2.137 \cdot 60.558 \cdot 10^{-4}}{0.121} = 107.0,$$

where:

thermal conductivity of oil [10] $\lambda_f = 0.121$ W/(m·K),
mean heat capacity of oil [10] $c_f = 2.137$ kJ/(kg·K).

Nusselt number is:

$$\mathrm{Nu} = \frac{\alpha_f d_w}{\lambda} = \frac{\alpha_f\, 0.025}{0.121} = 1.4 \cdot 128.4^{0.4} \cdot 107^{0.33} \left(\frac{0.025}{0.295}\right)^{0.4},$$

hence heat-transfer coefficient

$\alpha_f = 82.0$ W/(m^2·K).

Heat-transfer coefficient on air side
Velocity of air is:

$$w_a = \frac{V_a}{F_a} = \frac{0.365}{0.00317} = 11.5 \text{ m/s},$$

According to Schack [3] convective heat-transfer coefficient for smooth element is:

$$\alpha_o = \left(3.5 + 0.00185\, \bar{t}_a\right) \frac{w_a^{0.8}}{d_2^{0.2}} = \left(3.5 + 0.00185 \cdot 20.9\right) \frac{11.5^{0.8}}{0.052^{0.2}} = 45.4 \text{ W/(m}^2 \cdot \text{K)},$$

where:

outer diameter $d_2 = 0.052$ m,

mean temperature of air $\bar{t}_a = \dfrac{18.3 + 23.5}{2} = 20.9\ ^{\circ}\mathrm{C}$.

The surface area of fin is:

$$F_{\dot{z}} = 2\pi\left(r_2^2 - r_1^2\right) = 2\pi\left(0.026^2 - 0.015^2\right) = 0.00283 \text{ m}^2.$$

The surface area of smooth pipe on one pitch is:

$$F_r = 2\pi r_1 p = 2\pi \cdot 0.015 \cdot 0.00254 = 0.000239 \text{ m}^2.$$

The inner surface area of pipe is:

$$F_w = 2\pi r_w p = 2\pi \cdot 0.012 \cdot 0.00254 = 0.00191\ \text{m}^2.$$

The surface area between fins on one pitch is:

$$F_m = F_r - \pi d_1 s = 0.000239 - \pi \cdot 0.030 \cdot 0.00045 = 0.000197\ \text{m}^2.$$

The reduced convection heat-transfer coefficient is:

$$\alpha_r = \alpha\left(\frac{F_m}{F_r} + \frac{F_{\dot{z}}}{F_r}\eta\right) = 45.4\left(\frac{0.000197}{0.000239} + \frac{0.00283}{0.000239}\cdot 0.95\right) = 548.1\ \text{W/(m}^2\cdot\text{K)}.$$

The over-all heat transfer coefficient calculated by equations (3) and (4) is:

$$k = \frac{1}{\dfrac{\varphi_o}{\alpha_f} + \dfrac{1}{\alpha_r}} = \frac{1}{\dfrac{1.8}{82} + \dfrac{1}{548.1}} = 42.0\ \text{W/(m}^2\cdot\text{K)}.$$

where:

$$\varphi_o = \frac{F}{23 \cdot \pi d_1 \cdot l} = \frac{.15}{23 \cdot \pi \cdot 0.03 \cdot 0.295} = 1.8.$$

The heat-transfer ratio of heat exchanger is:

$$Q = V_a \cdot c_a\left(t_a'' - t_a'\right) = 0.365 \cdot 1.28\,(23.5 - 18.1) = 2.43\ \text{kW}.$$

The mean temperature difference is:

$$\Delta t_m = \bar{t}_f - \bar{t}_p = 68.4 - 20.9 = 47.5\ {}^{\text{o}}\text{C}.$$

The over-all heat-transfer coefficient calculated by equation (2) is:

$$k = \frac{Q}{F\Delta t_m} = \frac{2340}{1.15 \cdot 47.5} = 45.0\ \text{W/(m}^2\cdot\text{K)}.$$

The calculation error of over-all heat-transfer coefficient is:

$$\Delta = \frac{45 - 42}{45}\cdot 100\% = 6.7\%.$$

5. INFERENCES

- Model researches carried out on an experimental post and heat calculations make possible the identification of over-all heat-transfer coefficient in oil-air heat exchanger made of aluminium cross-finned pipes with circular fins.
- Difference of the value of over-all heat transfer coefficient calculated by simplified method and Mean Temperature Difference one comes to 6.7%.
- Influence efficiency of fin on heat transfer is described by the reduced heat transfer coefficient.
- The maximal difference between efficiency of fin calculated by three methods comes to 4.0%.
- Elaborated simplified method makes possible the identification of construction parameters and designed oil-air heat exchangers.

Acknowledgements

The financial support from the Polish Ministry of Science and Higher Education, contract AGH No. 11.11.110.935 is gratefully acknowledged.

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Received
October 2011