STUDY ON THE DETERMINATION OF THE OPTIMAL HEAT EXCHANGE TUBE TYPE FOR HYDRAULIC FLUID COOLERS IN HYDRAULIC EXCAVATORS

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ABSTRACT

Heat exchange tubes are the most critical components in hydraulic fluid coolers equipped with axial flow fans. The shape and cross-sectional dimensions of these tubes have a significant impact on the average heat transfer coefficient, heat dissipation capacity, pressure loss in both the hydraulic fluid flow and the convective airflow, as well as the geometric size of the cooler itself. The cross-sectional shapes of heat exchange tubes are highly diverse; however, most traditional oil coolers commonly use circular tubes, while oval heat exchange tubes have been adopted in the hydraulic fluid coolers of certain modern hydraulic machines. In this paper, the authors present the results of a computational and simulation-based study using Matlab-Simulink and SolidWorks Flow Simulation software to compare and determine the optimal shape and size of heat exchange tubes. The study focuses on two of the most widely used tube types today: circular tubes and flat oval tubes. The goal is to establish a scientific foundation for the successful design and manufacturing of compact axial-fan hydraulic fluid coolers with high thermal efficiency and large heat dissipation capacity, applicable to hydraulic systems in general, and particularly in open-pit hydraulic excavators.

Keywords: *Hydraulic fluid cooler, average heat transfer coefficient, hydraulic system, heat exchange tube, heat flux, pressure loss.*

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1. INTRODUCTION

Air-cooled heat exchangers offer numerous advantages, such as the use of natural ambient air as a cooling fluid, which is freely available and universally accessible, as well as simple design, low operating costs, safety, and environmental friendliness. Therefore, they have been widely applied in various industries including petrochemical refining, thermal power generation, chemical processing, machinery manufacturing, and mining hydraulic equipment. In the hydraulic systems of open-pit mining machinery, the main heat exchanger is the hydraulic fluid cooler (HFC), which serves the function of dissipating heat and establishing thermal equilibrium. It helps regulate and maintain the hydraulic oil temperature within the optimal operational range, thereby extending the service life of the oil and hydraulic components, reducing system failures, machine downtime, repair frequency, and replacement costs.

The cross-sectional shape, geometric dimensions, and arrangement parameters of heat exchange tubes (HETs) significantly affect the thermal performance, heat flux, hydrodynamic drag, pressure loss, frontal dimensions, and practical applicability of the HFC. Research into the optimal shape and size of the HETs contributes greatly to the development of compact, high-efficiency hydraulic fluid coolers with large heat transfer capacity, specifically designed for open-pit hydraulic excavators. A heat exchange tube is considered optimal when it simultaneously satisfies criteria such as high heat transfer efficiency, low hydraulic loss, compact size, light weight, commercial availability, ease of manufacturing during cooler fabrication, and low cost.

The fundamental theories of heat transfer and applied fluid dynamics remain incomplete, making it difficult to solve practical engineering problems using only theoretical methods. A limited number of researchers - such as V. A. Kondrashev, A. N. Ivanova [5], V. A. Kondratyuk [6], W. M. Kays, and A. L. London [4] have conducted experimental studies on this subject. However, these studies are constrained by their focus on specific tube geometries and a narrow range of Reynolds numbers (Re).

With the advancement of modern science and technology, complex differential equations related to heat transfer and applied fluid dynamics can now be solved using computational methods and specialized engineering software. The main advantages of digital simulation methods include the ability to perform "virtual experiments" with low investment costs, reduced computation time, and the capability to replicate real-world operating conditions. This increases the accuracy of simulation results and enables engineers to explore and compare multiple design alternatives efficiently. Results can be displayed in numerical and graphical formats, facilitating analysis and decision-making. In this study, we present the outcomes of research on selecting the optimal shape and size of heat exchange tubes for hydraulic fluid coolers using digital simulation methods through SolidWorks Flow Simulation and Matlab-Simulink software.

2. RESEARCH METHODOLOGY

2.1. Mathematical modeling

The selection of the optimal cross-sectional shape and dimensions of the heat exchange tubes in terms of heat transfer performance was conducted in two steps, using the SolidWorks Flow Simulation software: (1) Step one involves calculating, simulating, and comparing the heat dissipation capabilities (average heat transfer coefficient) of oval and circular HETs with the same external surface area, in order to determine the optimal tube shape; (2) Step two includes simulating and comparing the values of the average heat transfer coefficient of the most commonly used HET types, which meet the manufacturing standards for hydraulic fluid coolers and belong to the group of optimal-shaped tubes (as identified in step one).

To select the optimal HET in terms of hydraulic loss (i.e., the lowest pressure loss within the hydraulic fluid cooler), it is necessary to perform simulations and compare the pressure drops of several "virtual coolers" constructed from optimally shaped HETs of varying dimensions, using the Matlab-Simulink software. The simulation and comparison of pressure losses in the HFCs are presented through two design configurations: First, HFCs with an equal number of heat exchange tubes; Second, HFCs with equal air-side heat transfer surface area (i.e., coolers composed of smaller cross-sectional tubes require a larger number of tubes, and vice versa).

The pressure loss (Δp_l, Pa) in a heat exchange tube of length L_3 (m) is determined using the Darcy-Weisbach equation for viscous fluid flow [2, 3, 5]:

$$\Delta p_l = \frac{\rho_d}{2}\lambda\frac{L_3}{d_1}\overline{V}^2 \tag{1}$$

Where: ρ_d - density of the hydraulic fluid, (kg/m^3); λ - hydraulic friction coefficient; d_1- inner diameter of the heat exchange tube, (m); $\overline{V}$ - average flow velocity inside the heat exchange tube (m/s), which is determined as follows:

$$v_{cp} = \frac{G_d}{A_{in}.m.z} \tag{2}$$

here, G_d - volumetric flow rate of hydraulic fluid through the hydraulic fluid cooler, (m^3/s); A_{in} - internal cross-sectional area of the heat exchange tube, (m^2); m, z - number of tube columns and rows in the hydraulic fluid cooler; λ - hydraulic friction coefficient, which depends on the flow regime and is determined using the following empirical formulas:

+ For laminar flow, the hydraulic friction coefficient λ is calculated using the Poiseuille equation [2, 3]:

$$\lambda = \frac{64}{R_e} \tag{3}$$

+ For turbulent flow, the hydraulic friction coefficient λ is determined using the Blasius equation [2, 3]:

$$\lambda = 0.3164{R_e}^{-0.25} \tag{4}$$

where: $R_e = {\overline{V}.d_{эк}}/{v}$ - Reynolds number of the hydraulic fluid flow inside the heat exchange tube; v - kinematic viscosity, (m^2/s).

2.2. Computational block diagram

The computational block diagram - which explains the methodology and sequence of calculation steps to be carried out in the study - is presented in Fig. 1.

The variation of the kinematic viscosity of Shell Tellus-46 hydraulic fluid with temperature, in the range from 0°C to 110°C, is determined using the following algebraic expressions [6, 12, 13].

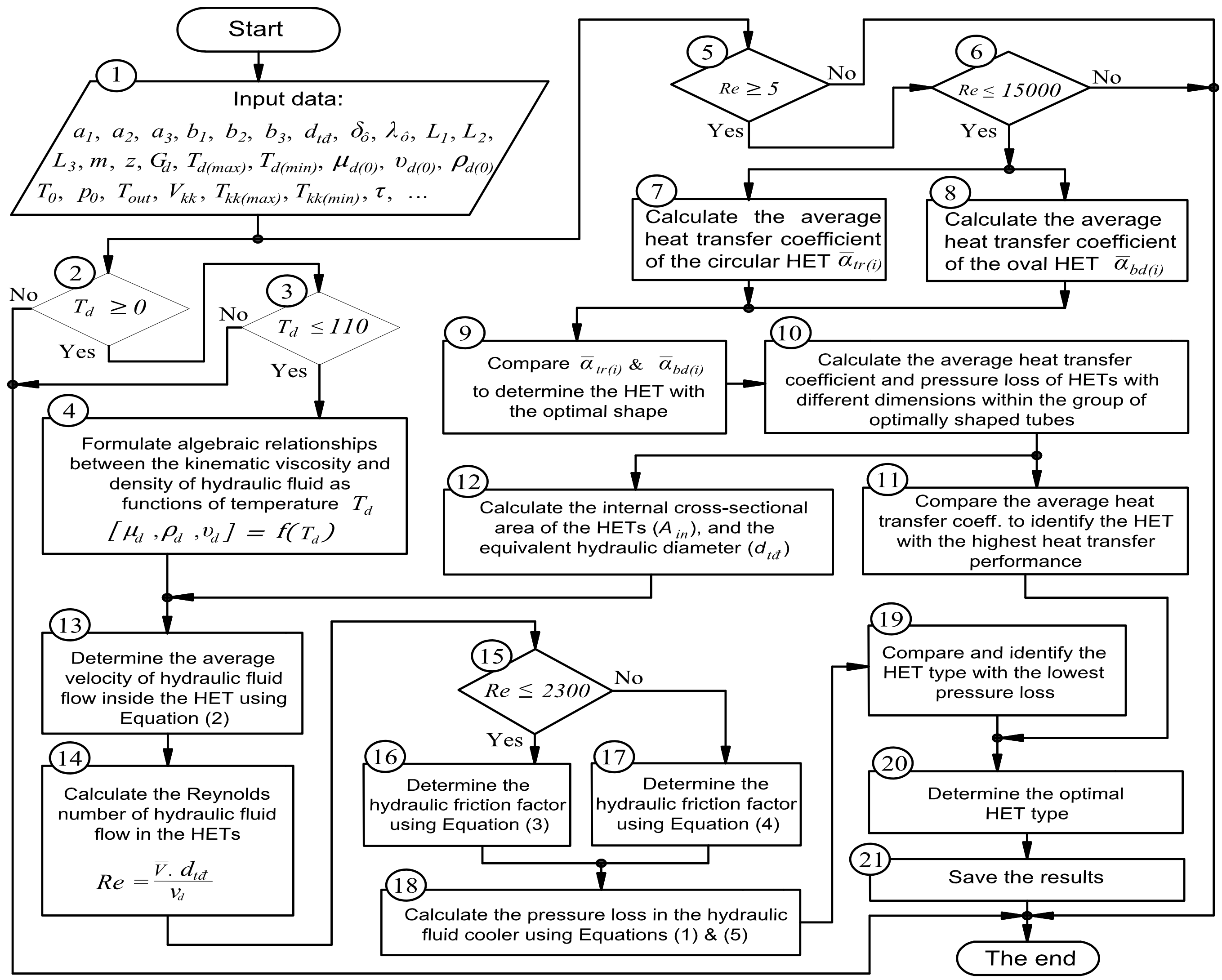


Fig. 1. Computational block diagram for determining the optimal heat exchange tube type for the hydraulic fluid cooler

Table 1. Kinematic viscosity equations of hydraulic fluid as a function of temperature

Temperature range, °C	Kinematic viscosity equation of hydraulic fluid as a function of temperature (T_d, °C)
[0÷10]	$v = 0.9T_d^2 - 30.5T_d + 430$
(10÷20]	$v = 0.6T_d^2 - 28T_d + 435$
(20÷30]	$v = 0.14T_d^2 - 11.3T_d + 285$
(30÷40]	$v = 0.04T_d^2 - 5.4T_d + 198$
(40÷110]	$46^{\left(40/T_d\right)^{0.559}}$

The total pressure loss in the hydraulic fluid cooler during the operation of the excavator's hydraulic system is determined by the following expression:

$$\Delta p_{BLMD} = \sum_{i=1}^{N} \Delta p_l = mz\Delta p_l \quad (5)$$

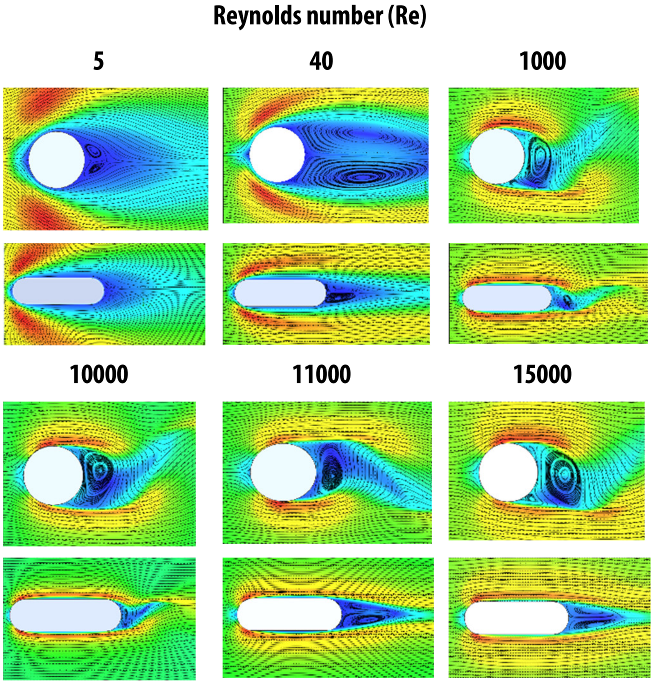
Where: N = m.z is the total number of heat exchange tubes in the hydraulic fluid cooler.

3. RESULTS AND DISCUSSION

The main parameters applied for calculation and simulation were referenced from the hydraulic fluid cooler (HFC) of the Komatsu PC750SE-7 open-pit hydraulic excavator and Shell Tellus S2V-46 hydraulic fluid [14,15]: the heat exchange tubes are made of aluminum alloy; the average velocity of the airflow at the front of the HFC is 5.5m/s; the ambient air temperature in the working environment is T_0 = 27.2°C (corresponding to the average annual temperature in Vietnam), and the air pressure generated by the cooling fan is p_0 = 102.275Pa; the outer surface temperature of the heat exchange tubes is T_0(out) = 70°C; the temperature range of the hydraulic fluid is T_d = (0 ÷ 110)°C; the volumetric flow rate of the hydraulic fluid through the cooler is $G_d = 8.582\times10^{-6}m^3/s$; the length of one heat exchange tube is L_3 = 1190mm; the total number of heat exchange tubes in the cooler, using a tube with an aspect ratio $a_3/b_3 = 21/6$, is N = 87×3 = 261; three oval tube types were studied, with major-to-minor axis ratios of $a_1/b_1 = 9/6 = 1{,}5$; $a_2/b_2 = 15/6 = 2{,}5$; $a_3/b_3 = 21/6 = 3{,}5$; the circular heat exchange tube has a diameter of d_{td} = 15.6mm; and the wall thickness of all tubes is δ_o = 0.75mm, ect.

The simulation results of airflow around circular heat exchange tubes with a diameter of d_{td} = 15.6mm nd oval tubes with the same external heat dissipation surface area and a major-to-minor axis ratio of a/b = 21/6 are presented in Table 2.

Table 2. Airflow around heat exchange tubes at different Reynolds number (Re) values



The calculated results of the average heat transfer coefficient ($\overline{\alpha}_0$, $W/(m^2.°C)$) for circular and oval heat exchange tubes in this case are presented in Fig. 2.

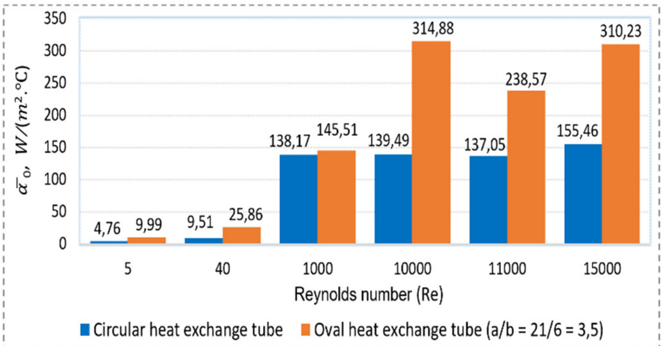


Fig. 2. Average heat transfer coefficient of heat exchange tubes

Based on the results presented in Table 2 and Fig. 2, we observe that:

+ The vortex region behind the circular heat exchange tube is significantly larger than that of the oval tube. The direction of airflow within the vortex opposes the direction of the cooling airflow through the hydraulic fluid cooler, and this, combined with the high static pressure in the rear zone, results in considerable aerodynamic drag. Additionally, the extended wake region behind the circular tube reduces the heat dissipation capability of downstream tube rows in the direction of airflow across the HFC;

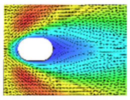
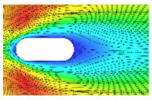
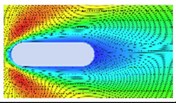
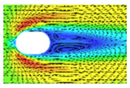
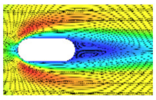
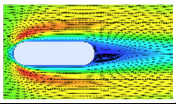
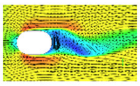
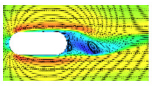
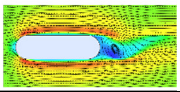
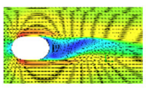
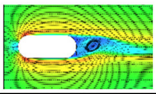
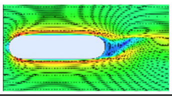
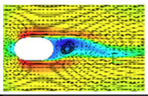
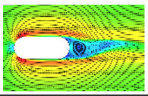
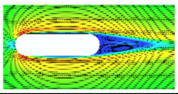
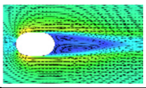
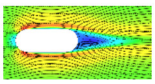
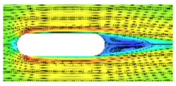
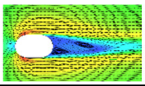
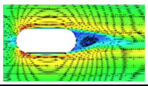
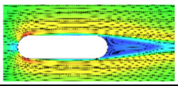
+ Within the Reynolds number range of Re = (5 ÷ 1.5×10^4), the average heat transfer coefficient ($\overline{\alpha}_0$) of the oval tube is consistently higher than that of the circular tube with the same external surface area and at the same Reynolds number. This indicates that the oval tube has a more optimal geometry for heat transfer compared to the circular tube of equivalent external surface area;

+ An HFC constructed using oval heat exchange tubes will have a smaller frontal width dimension (L_1, m) - by approximately 15.6/6 = 2.6 times - compared to one made with circular tubes having the same air-side heat transfer area. This finding is highly significant, as it supports the design of compact HFCs suitable for hydraulic systems in excavators and other open-pit mining hydraulic machinery.

Heat exchange tubes are manufactured under various standards regarding material, shape, geometric dimensions, and mechanical strength. Different tube types or even tubes of the same type but with different geometries exhibit distinct thermal performance and hydro-aerodynamic resistance characteristics. If the volumetric flow rate through the tubes is equal, smaller cross-sectional tubes will cause higher hydraulic losses and pose difficulties in fabrication during cooler manufacturing. In contrast, larger cross-sectional tubes produce lower internal hydraulic resistance but greater external aerodynamic drag. Therefore, this section performs calculations and comparisons to identify the optimal oval tube size that balances both heat transfer efficiency and hydraulic pressure loss. Oval tubes with the same major-to-minor axis ratio (a/b) are considered geometrically similar and are assumed to have the same heat transfer characteristics [1]. The simulated airflow characteristics around oval tubes with axis ratios a/b = 21/6, 15/6, and 9/6 are presented in Table 3.

The calculated results of the average heat transfer coefficient ($\overline{\alpha}_0$) for the oval heat exchange tubes are shown in Fig. 3.

Table 3. Airflow around oval heat exchange tubes at different Reynolds number values

Re \ a/b	1.5	2.5	3.5
5			
40			
10^3			
10^4			
1.1×10^4			
1.5×10^4			
2×10^4			

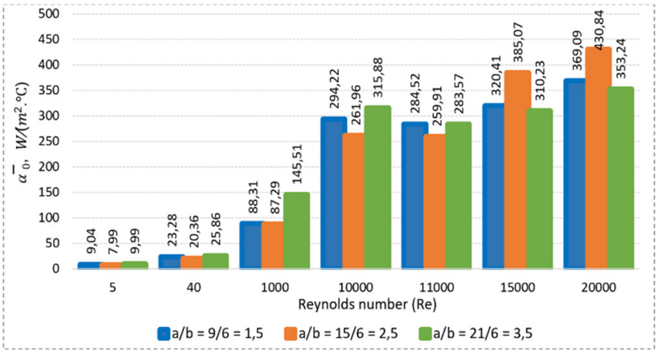


Fig. 3. Average heat transfer coefficient ($\overline{\alpha}_0$) of three types of oval tubes with different aspect ratios

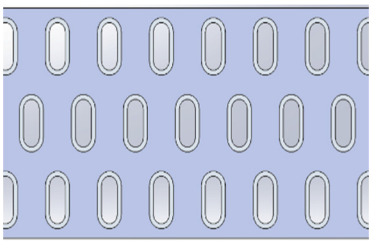
According to the calculation and simulation results presented in Fig. 3, it can be observed that:

+ Within the Reynolds number (Re) range from 5 to 10000, the oval tube with a major-to-minor axis ratio of a/b = 3.5 consistently exhibits the highest average heat transfer coefficient. This indicates that, in this Reynolds number range, the oval tube with an aspect ratio of a/b = 3.5 provides the best heat dissipation performance;

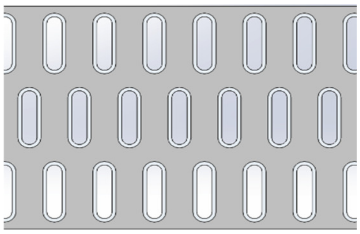
+ Within the Reynolds number (Re) range from 10000 to 20000, the average heat transfer coefficient of the oval tube with an aspect ratio of a/b = 3.5 is unstable and the lowest among the three types of heat exchange tubes studied. In this range, the oval tube with an aspect ratio of a/b = 2.5 exhibits the highest average heat transfer coefficient. However, this Reynolds number range is only practically relevant when designing hydraulic fluid coolers in which the average velocity of the cooling airflow generated by the fan exceeds v > 29m/s.

When the hydraulic system operates, the entire volume of hydraulic fluid flows through the hydraulic fluid cooler to be cooled - reducing its temperature - before returning to the oil tank (open-loop circulation system). Due to viscous friction, the flow of hydraulic fluid inside the heat exchange tubes of the cooler generates a pressure loss. The type of heat exchange tube that produces the lowest pressure loss is considered superior in terms of hydraulic loss performance. The calculation and selection of the optimally sized heat exchange tube with respect to hydraulic pressure loss, from among the three oval tube types with axis ratios of a/b = 9/6, 15/6, and 21/6, are carried out under the following two design scenarios:

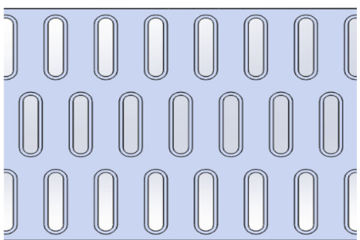
* ***Option 1***: Three hydraulic fluid coolers are constructed using three types of oval tubes with major-to-minor axis ratios of a/b = 9/6, 15/6, and 21/6, respectively (Fig. 4).



a/b = 9/6



a/b = 15/6



a/b = 21/6

Fig. 4. Cross-sectional view of a portion of hydraulic fluid coolers with three staggered rows of oval tubes

The number of tube rows and columns in the three hydraulic fluid coolers is the same, with $z_1 = z_2 = z_3 = 3$ and $m_1 = m_2 = m_3 = 87$, meaning that the total number of heat exchange tubes in each cooler is 87 × 3 = 261. The calculated and simulated results of pressure loss in the three coolers under Design Option 1 are presented in Fig. 5 and Table 4.

* **Option 2**: The internal wetted cross-sectional areas of the oval tubes with aspect ratios of 21/6, 15/6 and 9/6 are 83.4mm^2; 56.4mm^2 and 29.4mm^2. To ensure that the total internal flow area for hydraulic fluid is equal across all three hydraulic fluid coolers, the number of tubes with smaller cross-sections must be increased. Accordingly, the number of oval heat exchange tubes with aspect ratios of 21/6, 15/6, and 9/6 in the coolers will be: 3×87 = 261; $83{,}4/56{,}4 \times 3 \times 87 = 386$ and $83{,}4/29{,}4 \times 3 \times 87 = 740$. As a result, the number of tube rows (z) for the coolers using oval tubes with aspect ratios of 21/6, 15/6, and 9/6 will be: $z_1 = 3$, $z_2 = 5$ and $z_3 = 9$. The calculated and simulated results of total hydraulic loss for the coolers under Design Option 2 are shown in Fig. 6 and in Table 4.

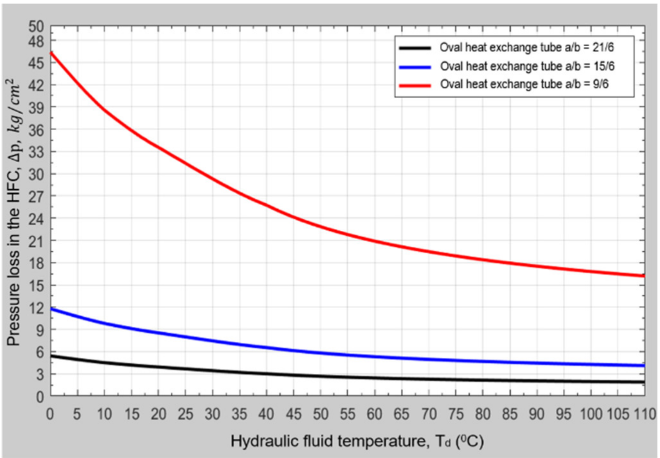


Fig. 5. Total pressure loss in the HFC in option 1

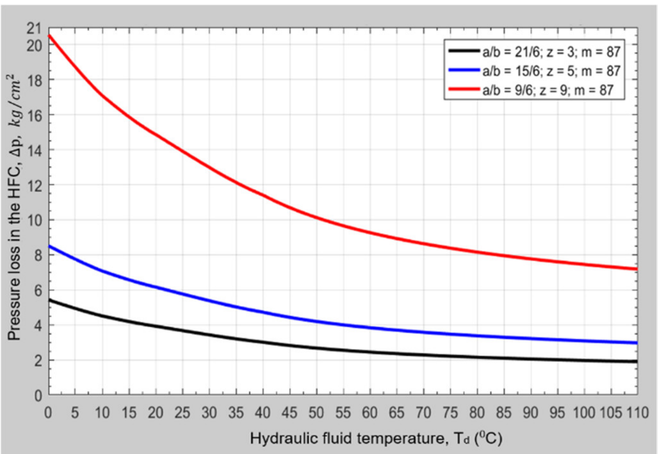


Fig. 6. Total pressure loss in the HFC in option 2

The variation in total internal pressure loss of the hydraulic fluid coolers constructed with oval heat exchange tubes of different sizes, as a function of hydraulic fluid temperature in the range from 0 °C to 110 °C, for both Option 1 and Option 2, is presented in Table 4.

Table 4. Total internal pressure loss of the hydraulic fluid cooler

Temperature of the hydraulic fluid (T_d, °C)	Total pressure loss in the HFC in option 1 (Δp, kg/cm^2)			Total pressure loss in the HFC in option 2 (Δp, kg/cm^2)		
	9/6	**15/6**	**21/6**	**9/6**	**15/6**	**21/6**
0	46.25	11.73	5.37	20.85	8.58	5.37
10	38.57	9.80	4.51	17.65	7.31	4.51
20	33.55	8.53	3.92	15.35	6.36	3.92
30	29.31	7.45	3.43	13.41	5.55	3.43
40	25.74	6.54	3.01	11.78	4.88	3.01
50	22.84	5.80	2.67	10.45	4.33	2.67
60	20.89	5.31	2.44	9.55	3.96	2.44
70	19.48	4.95	2.28	8.92	3.69	2.28
80	18.39	4.67	2.14	8.42	3.48	2.14
90	17.51	4.45	2.04	8.02	3.32	2.04
100	16.79	4.27	1.96	7.69	3.18	1.96
110	16.22	4.12	1.89	7.45	3.08	1.89

Based on the calculation and simulation results shown in Figs. 5, 6 and Table 4, we observe that:

\+ The hydraulic fluid cooler constructed using oval heat exchange tubes with an aspect ratio of 21/6 in both design option 1 and design option 2 exhibits the lowest total pressure loss within the hydraulic fluid operating temperature range from 0°C to 110°C (black characteristic curve);

\+ From Fig. 6 and Table 4, it can be seen that in design option 2, the hydraulic fluid coolers constructed with oval heat exchange tubes having aspect ratios of 15/6 and 9/6 exhibit lower total pressure losses compared to design option 1; however, the pressure loss values still remain relatively high.

Through the analysis of the calculated and simulated results presented in Figs. 2, 3, 5, 6 and Table 4, it is observed that within the Reynolds number range below 10000, the oval heat exchange tube with an aspect ratio of a/b = 21/6 = 3,5 is the optimal choice for designing a compact hydraulic fluid cooler for the hydraulic system of open-pit mining excavators.

4. CONCLUSION

1. Within the Reynolds number range of Re = (5 ÷ 15 000), the average heat transfer coefficient of oval heat exchange tubes is consistently higher than that of circular tubes with the same external heat transfer surface area.

2. Replacing circular heat exchange tubes with oval tubes of equal external surface area reduces the frontal width (L_1) of the hydraulic fluid cooler by approximately 2.6 times.

3. In the Reynolds number range from 5 to 10 000 and hydraulic fluid temperature range from 0°C to 110°C, oval tubes with an aspect ratio of 21/6 exhibit the highest average heat transfer coefficient and the lowest internal pressure loss compared to those with aspect ratios of 15/6 and 9/6.

4. Oval heat exchange tubes with the same major-to-minor axis ratio (a/b) are considered geometrically similar and therefore possess equivalent heat transfer characteristics [1]. Thus, the findings of this study can be applied to heat transfer calculations for all oval tubes with the same axis ratio.

5. This study has identified the optimal shape and size of the heat exchange tube. However, further research is needed to investigate the effects of transverse and longitudinal pitch (S_1, S_2) and the number of tube rows (z) as a foundation for the successful development of compact hydraulic fluid coolers with high thermal efficiency and large heat dissipation capacity.

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