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Effect of Fluid Types on the Performance of Heat Exchanger Base on Flow Configurations

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***Abstract**: An application software for evaluating heat exchanger performance considering four different types of flow configurations is developed in this study. Standard physical heat transfer model was devised by applying the concept of energy balance to the outlet temperature for both hot and cold fluid portion of the system. The models implemented in MATLAB R2018b was used to estimate numerically the heat exchanger performance in terms of effectiveness (ε) and heat transfer rate (Q). In all the flow configuration considered in this work, an increase in heat exchanger effectiveness is observed with increase in mass flow rate consequently, in comparison to other flow configurations such as: parallel flow, cross flow and shell and tube at n=1, the counter flow configuration gave best thermal performance with the heat exchanger effectiveness value range from 1.036 to 1.059. Among the refrigerants simulated in the selected heat exchanger system flow configuration under similar operating conditions, the heat exchanger system independently of the flow configurations with the use of methanol and ammonia yields best thermal performance with the highest value of 0.98 for methanol and 88.7 kW for ammonia in terms of effectiveness and heat transfer rate enhancement respectively. The results obtained from the numerical analyses were in good agreement with the experiments data obtained from literature with the discrepancies of the heat transfer rate and effectiveness estimated to be less than 11.63% and 1.55% respectively. It can be concluded that methanol and ammonia may act as a better substitute to the green offensive refrigerants commonly used in refrigeration system, thus helping to solve the ozone depletion potential (ODP) and global warming potential (GWP) problems regarding environmental impact issues.*

Keywords: *Flow configurations, effectiveness, heat transfer rate, refrigerants heat exchanger performance.*

1. INTRODUCTION

In sustaining a healthy and optimal operation of any thermal system, it is expedient that heat dissipation should be maximally maintained. One of the technical means of achieving this objective is through the use of heat exchanger device. A heat exchanger is a device which is used to transfer thermal energy between two or more fluid, between a solid surface and a fluid, or between solid particulates and a fluid, at different temperatures in thermal contact [1]. Heat exchangers are widely used in automobile, aerospace, cryogenic, chemical industries, electric power plants, propulsive power plants and systems with thermodynamic cycles i.e. heat pump, refrigeration, electronic, gas-liquefaction, air-conditioning, waste heat recovery systems.

[2] reported that heat exchangers can be classified on the basis of their mechanism properties such as double pipe, shell and tube, spiral tube, gasket, spiral plate, lamella, compact, finned plate and finned tube heat exchangers. On the basis of constructional details, heat exchanger is also classified into tubular, plate-type, extended surface (fins) and regenerative type heat exchangers [3]. According to [1], heat exchangers can also be classified in accordance with their flow arrangements which are parallel-flow, counter-flow and cross-flow. However, the authors reported that, independently of their classification, heat exchangers are characterized base on their effectiveness, compactness, weight and cost which are functions of their respective applications. Many problems arise from the literature that involves the use of fluid parameters to determine the maximum condition of operation of heat exchangers. [4] made an attempt to experimentally analyze the performance of shell and tube type cross counter flow heat exchanger by changing the various parameters like both hot and cold fluid flow rate, direction of fluid flow. [5] investigated the performance of unmixed-unmixed cross flow heat exchanger with different flow rate and different composition of hot fluid. The effect of these parameters on outlet temperatures and overall heat transfer coefficient were studied. [6] investigated entransy effectiveness for analysis of heat exchangers, the effect of changing the number of transfer units (NTU), on entransy effectiveness for heat exchanger was discussed. [7] presented a paper on heat transfer and effectiveness analysis based on a physical model of a cross-flow heat exchanger with

air as working fluid. Using the model, the transferred heat and effectiveness (ε) in terms of temperature and NTU-method are calculated for both hot and cold streams. [8] reported a work on the design and construction of a concentric tube heat exchanger which was designed in order to study the process of heat transfer between two fluids through a solid partition. [9] presented a study which deals with the experimental evaluation of effectiveness of counter flow mini channel heat exchangers for circular cross-sectional geometry. The heat transfer fluids used in the mini channel heat exchanger are oil (SAE20W40) and water. Low Reynolds number flow is found in the heat exchanger. A comparison between water and SAE20W40 oil was made and it was found that water served as a better heat transfer fluid than oil. Still oil was found as a better option at higher temperatures at which water will vaporize.

Despite the numerous experimental studies have been carried out to investigate performance of heat exchanger, they are still limited in making optimum design judgement due to equipment cost and time involved in carrying out such experiments. Additionally, majority of work carried out in order to study the condition for maximum performance of heat exchanger majorly considered working fluids such as: water, oil and air, depicts that further study is needed for better understanding of the heat exchanger thermal performance considering the effect of more fluid types and flow configuration. Therefore, to design or to predict the performance of a heat exchanger, an application software that could help to determine the effectiveness, NTU and the outlet temperatures of the heat exchanger taking into consideration the properties of heat exchanger components and the fluid parameters with different fluid types is developed in this study.

2. RESEARCH METHODOLOGY

2.1 The Software Design Parameters

The following input parameters are considered in the development of the prescribed software program; fluid types, inlet temperature for hot and cold fluid, mass flow rate, the heat transfer surface area, overall heat transfer coefficient, configuration of flow and number of shell. The targets are to determine the effectiveness, the heat transfer rate, number of heat transfer unit and the outlet temperature of both hot and cold fluids thus, obtaining the heat exchanger capacity for an expected heat dissipation requirement independent of the heat exchanger flow configuration arrangement.

2.2.1) Analysis of Heat Exchanger

Heat exchangers transfer heat from one working fluid to another. The heat transfer rate across a heat exchanger is mathematically expressed in Eq. (1)

$$Q = \dot{m}_c c_{pc} (T_{c,out}-T_{c,in}) \text{ and } Q = \dot{m}_h c_{ph} (T_{h,in}-T_{h,out}) \quad (1)$$

where,

$\dot{m}_c$ and $\dot{m}_h$ are the mass flow rates of cold and hot fluid respectively

c_{pc} and c_{ph} are the specific heats of cold and hot fluid respectively

$T_{c,out}$ and $T_{h,out}$ are the outlet temperatures of cold and hot fluid respectively

$T_{c,in}$ and $T_{c,in}$ are the inlet temperatures of cold and hot fluid respectively

In heat exchanger analysis, it is often convenient to combine the product of the mass flow rate and the specific heat of a fluid into a single quantity. This quantity is called the heat capacity rate and is defined for the hot and cold fluid streams as follows:

$$C_h = \dot{m}_h c_{ph} \text{ and } C_c = \dot{m}_c c_{pc} \quad (2)$$

Substituting Eq. (2) into (1) we have:

$$Q = C_c (T_{c,out}-T_{c,in}) \text{ and } Q = C_h (T_{h,in}-T_{h,out}) \quad (3)$$

In an analogous manner to Newton's law of cooling, the rate of heat transfer can also be express as follows:

$$Q = UA_s\Delta T_m \quad (4)$$

where:

Q is the heat transfer rate

U is the overall heat transfer coefficient

A is the heat exchanger surface area

ΔT_m is the average temperature difference between the fluids

2.3 Numerical Solution Procedure

The effectiveness method approach of heat exchanger analysis was used in the development of the computer application software. Valuable information are searched and gathered, the fluids are limited to water; engine oil, glycerin, methanol, air and ammonia, based on the availability and the economical values, various analysis for determination of heat transfer rate, effectiveness, NTU, outlet temperature of both hot and cold fluid are carried out with the variation of input parameters like overall heat transfer coefficient, mass flow rate of the fluids, area of heat exchangers and the inlet temperature of the fluids on parallel, counter, cross (mixed and unmixed) and shell and tube heat exchangers. It was assumed that the fluids are at constant room temperature.

2.3.1 Mathematical Model for the Heat Exchanger Effectiveness (NTU Method)

To ease determination of the heat transfer rate, heat exchangers effectiveness and the outlet temperatures of the hot and cold fluids for prescribed fluid mass flow rates and inlet temperatures when the type and size of the heat exchanger are specified, NTU Method is adopted in this study taking into considerations the following assumptions:

i. The heat exchanger and the tube curves are adiabatic

ii. The mixed fluid inlet conditions are homogenous for each element
iii. Specific heat is constant at room temperature

2.3.2) Determination of Heat exchanger effectiveness (ε)

The heat exchanger effectiveness, ε, is estimated using Eq. (5) defined as the ratio of the actual heat transfer rate for a heat exchanger to the maximum possible heat transfer rate:

$$\varepsilon = \frac{Q}{Q_{max}} = \frac{Actual\ heat\ transfer\ rate}{Maximum\ possible\ heat\ tranfer\ rate} \qquad (5)$$

The actual heat transfer rate in a heat exchanger is calculated using Eq. (3)
The maximum possible heat transfer rate in a heat exchanger is obtained as follows:

$$Q_{max} = C_{min}\Delta T_{max} \qquad (6)$$

where,

$$\Delta T_{max} = T_{h,in} - T_{c,in} \qquad (7)$$

C_{min} is the smaller of $C_h = \dot{m}_h c_{ph}$ and $C_c = \dot{m}_c c_{pc}$, given in Eq. (2)
The effectiveness of a heat exchanger enables us to determine the heat transfer rate without knowing the outlet temperatures of the fluids.

2.3.3) Determination of Heat Exchanger Number of Heat Transfer Unit (NTU)

The value of NTU is a measure of the heat transfer surface area A_s i.e, the larger the NTU the larger the heat exchanger. The NTU for the heat exchangers is obtained using Eq. (8)

$$\text{NTU} = \frac{UA_s}{C_{min}} = \frac{UA_s}{(\dot{m}c_p)_{min}} \qquad (8)$$

Where U is the overall heat transfer coefficient and A_s is the heat transfer surface area of the heat exchanger. In heat exchanger analysis, it is also convenient to define another dimensionless quantity called the capacity ratio C given as:

$$\text{C} = \frac{C_{min}}{C_{max}} \qquad (9)$$

Present in Table 1 are the considered heat exchanger effectiveness relations used in this study
Table 1: Effectiveness relations for heat exchangers

Heat exchanger types	Effectiveness relation
1. Double pipe	
a. Parallel flow	$\varepsilon = \frac{1 - \exp[-\text{NTU}(1 + \text{C})]}{1 + \text{C}}$
b. Counter flow	$\varepsilon = \frac{1 - \exp[-\text{NTU}(1 - \text{C})]}{1 - \text{C}\exp[-\text{NTU}(1 - \text{C})]}$
2. Shell and tube: One-shell pass 2, 4, … tube pass	$\varepsilon = 2\left\{1 + \text{C} + \sqrt{1 + C^2}\frac{1 + \exp\left[-\text{NTU}\sqrt{1 + C^2}\right]}{1 - \exp\left[-\text{NTU}\sqrt{1 + C^2}\right]}\right\}^{-1}$
3. Cross-flow (Single-pass) Both fluid Unmixed	$\varepsilon = 1 - \exp\left\{\frac{\text{NTU}^{0.22}}{\text{C}}[\exp(-\text{CNTU}^{0.78}) - 1]\right\}$
C_{max} mixed C_{min} unmixed	$\varepsilon = \frac{1}{\text{C}}(1 - \exp\{1 - \text{C}[1 - \exp(-\text{NTU})]\})$
C_{min} mixed C_{max} unmixed	$\varepsilon = 1 - \exp\left\{-\frac{1}{\text{C}}[1 - \exp(-\text{CNUT})]\right\}$
4. All heat exchangers with C=0	$\varepsilon = 1 - \exp(-\text{NUT})$

2.3.4 Determination Heat Exchanger Overall Heat Transfer Coefficient (U)

The overall heat transfer coefficient represents the total resistance to heat transfer from one fluid to another in the heat exchanger. In the analysis of heat exchangers, it is convenient to combine all the thermal resistances in the path of heat flow from the hot fluid to the cold one into a single resistance R as follows:

$$\mathrm{R} = R_{total} = R_i + R_{wall} + R_o = \frac{1}{h_i A_i} + \frac{In\,(D_o/D_i)}{2\pi k L} + \frac{1}{h_o A_0} \tag{10}$$

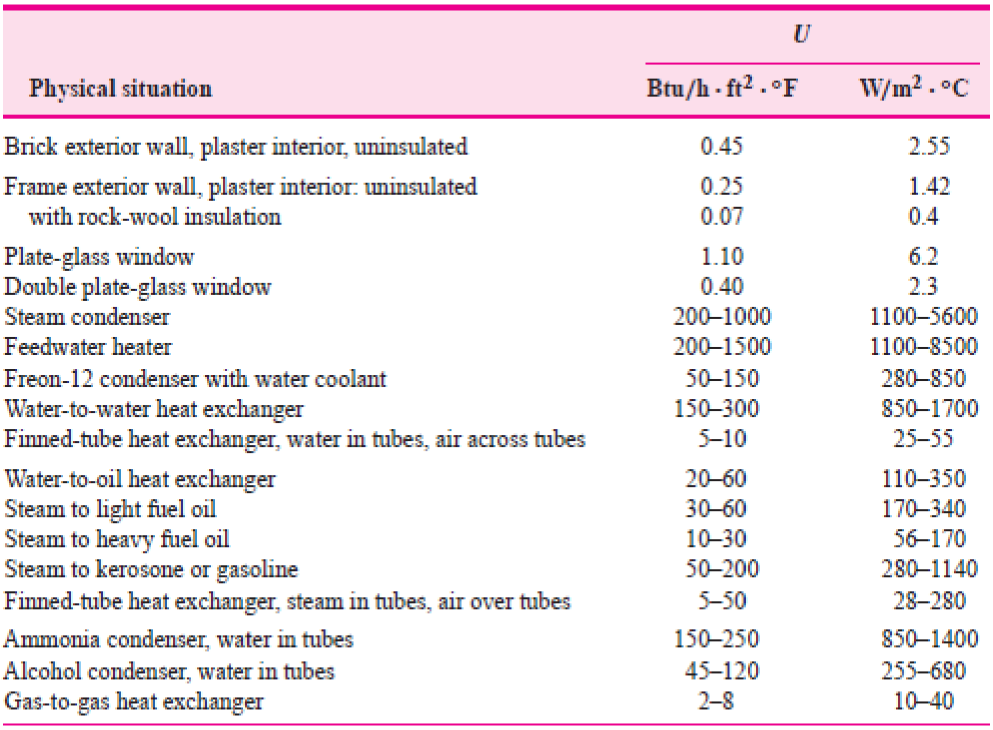
Where, k is the thermal conductivity of the wall material, L is the length of the tube,
h_i and h_o are convection heat transfer coefficients inside and outside the tube respectively.
$A_i = D_i L$ and $A_o = D_o L$ are surface areas of the separating wall wetted by the inner and the outer fluids, respectively.
In an analogous manner to Newton's law of cooling, the rate of heat transfer between the two fluids is express as follows:

$$Q = \frac{\Delta T}{R} = UA\Delta T = U_i A_i \Delta T = U_o A_o \Delta T \tag{11}$$

Removing ΔT in equation (11), we have:

$$\frac{1}{UA_s} = \frac{1}{U_i A_i} = \frac{1}{U_o A_o} = \mathrm{R} = \frac{1}{h_i A_i} + R_{wall} + \frac{1}{h_o A_0} \tag{12}$$

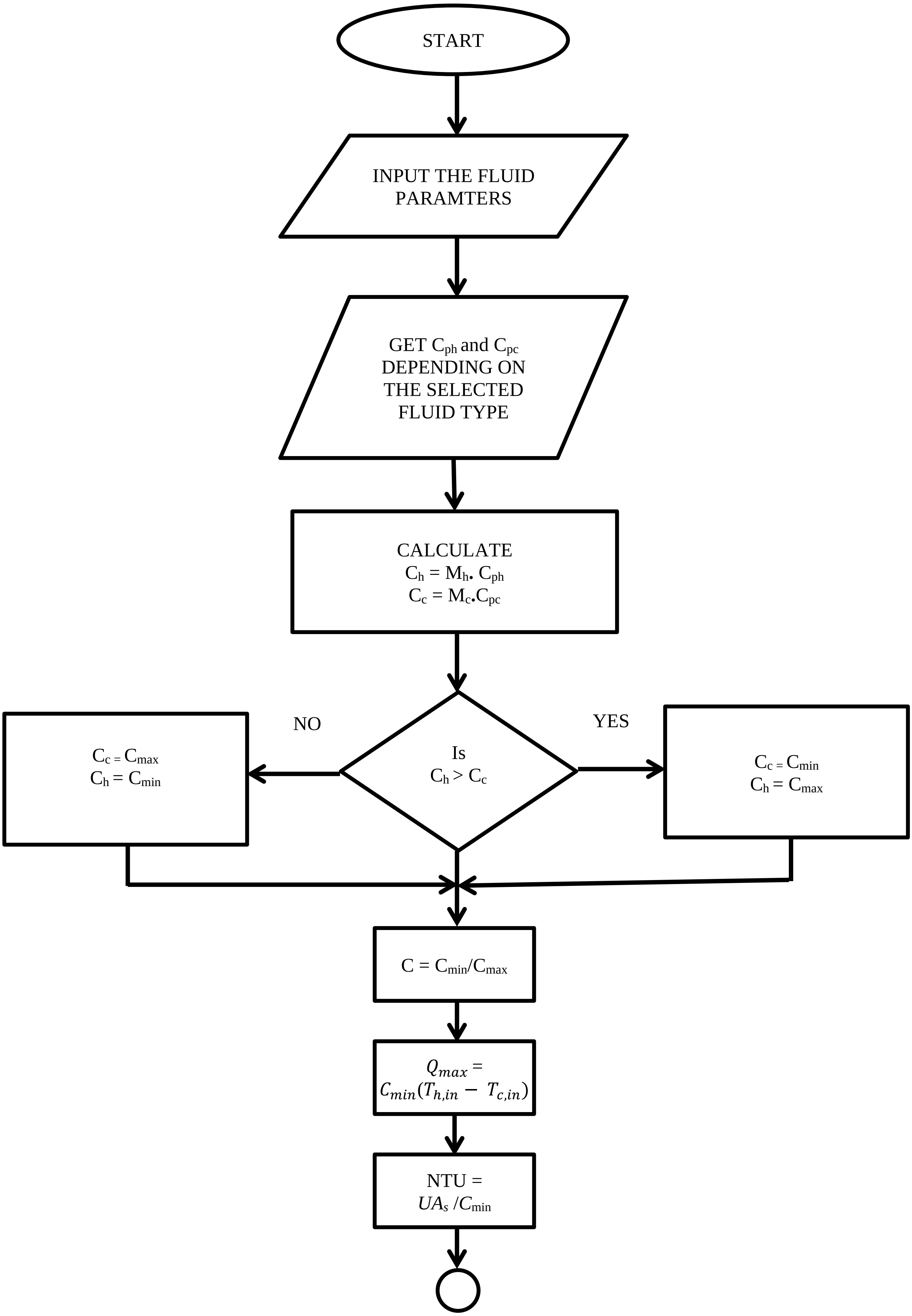
Where U is the overall heat transfer coefficient
Approximate values of overall heat-transfer coefficients according to [10] are as presented in Table 2
Table2 : Values of overall heat-transfer coefficients



Physical situation	*U*	
	Btu/h · ft^2 · °F	W/m^2 · °C
Brick exterior wall, plaster interior, uninsulated	0.45	2.55
Frame exterior wall, plaster interior: uninsulated	0.25	1.42
with rock-wool insulation	0.07	0.4
Plate-glass window	1.10	6.2
Double plate-glass window	0.40	2.3
Steam condenser	200–1000	1100–5600
Feedwater heater	200–1500	1100–8500
Freon-12 condenser with water coolant	50–150	280–850
Water-to-water heat exchanger	150–300	850–1700
Finned-tube heat exchanger, water in tubes, air across tubes	5–10	25–55
Water-to-oil heat exchanger	20–60	110–350
Steam to light fuel oil	30–60	170–340
Steam to heavy fuel oil	10–30	56–170
Steam to kerosone or gasoline	50–200	280–1140
Finned-tube heat exchanger, steam in tubes, air over tubes	5–50	28–280
Ammonia condenser, water in tubes	150–250	850–1400
Alcohol condenser, water in tubes	45–120	255–680
Gas-to-gas heat exchanger	2–8	10–40

2.4 Algorithm for the Computation of the Heat Exchanger Performance Output

The standard heat transfer equations given by Eqns. 1 to 12 were implemented in MATLAB R2018b with a view to simulate simple and complex geometries involving multi-pass parallel and counter flow and cross-flow heat exchangers with several circuit arrangement configurations. Based on the sorted standard heat transfer equations program algorithm flow chart shown in Figure 1 was prepared in this work considering the input parameters such as: the type of fluids, the inlet temperatures, the mass flow rates, the heat transfer surface area, the overall heat transfer coefficient and the type of heat exchanger to obtain the output parameters such as: the outlet temperature distributions, NTU, effectiveness and the heat transfer rate of the heat exchanger. This procedure allows computation of various parameters like ε-NTU relations, cold and hot fluid temperature distributions, heat transfer area, number of heat transfer unit, mass flow rate of cold and hot fluids, overall heat transfer coefficient and heat transfer rate independent of the flow arrangement as shown in Figure 2


START
INPUT THE FLUID PARAMTERS
GET C_{ph} and C_{pc} DEPENDING ON THE SELECTED FLUID TYPE
CALCULATE
$C_h = M_h . C_{ph}$
$C_c = M_c . C_{pc}$
Is $C_h > C_c$
NO
YES
$C_c = C_{max}$
$C_h = C_{min}$
$C_c = C_{min}$
$C_h = C_{max}$
$C = C_{min}/C_{max}$
$Q_{max} = C_{min}(T_{h,in} - T_{c,in})$
NTU = UA_s / C_{min}

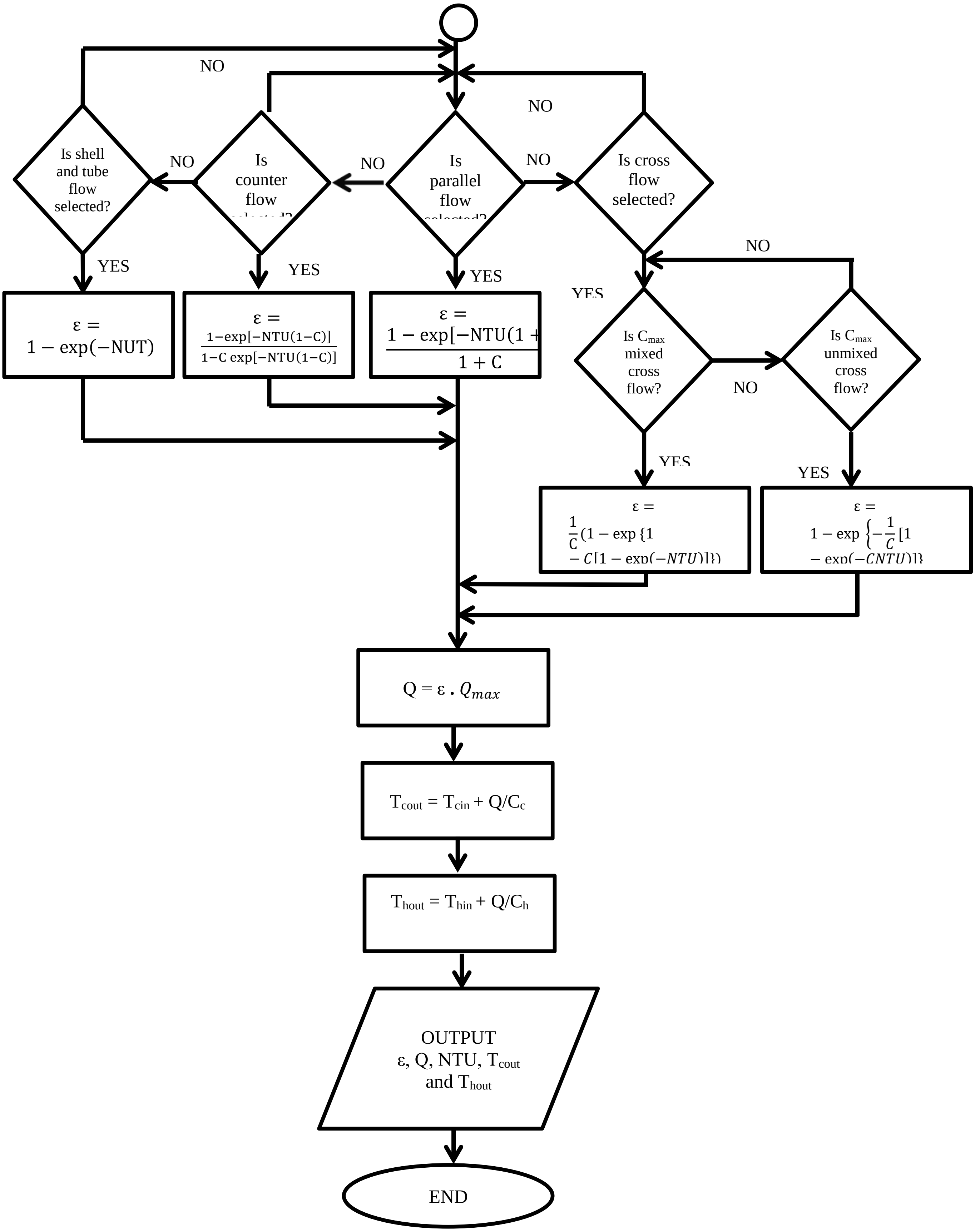


Figure. 1: The flow chart for the algorithm

Figure 2 The interface of the developed application software

3. RESULTS AND DISCUSSION

3.1 Validation of the Developed Application Software

The application software developed for heat exchanger analyzer in the present work is validated by comparing the numerical solution result obtained base on the use of the developed software with the experimental results from the work of [5]. Figure. 3. shows the comparison results between the present study numerical estimated values and the experimental values from the work of [5]. According to figure 3, the comparison results show very good agreement between the present study numerical solution results and the experimental results from the research work of [5] predicting 95% of their attained experimental data within an absolute mean deviation of 30%.

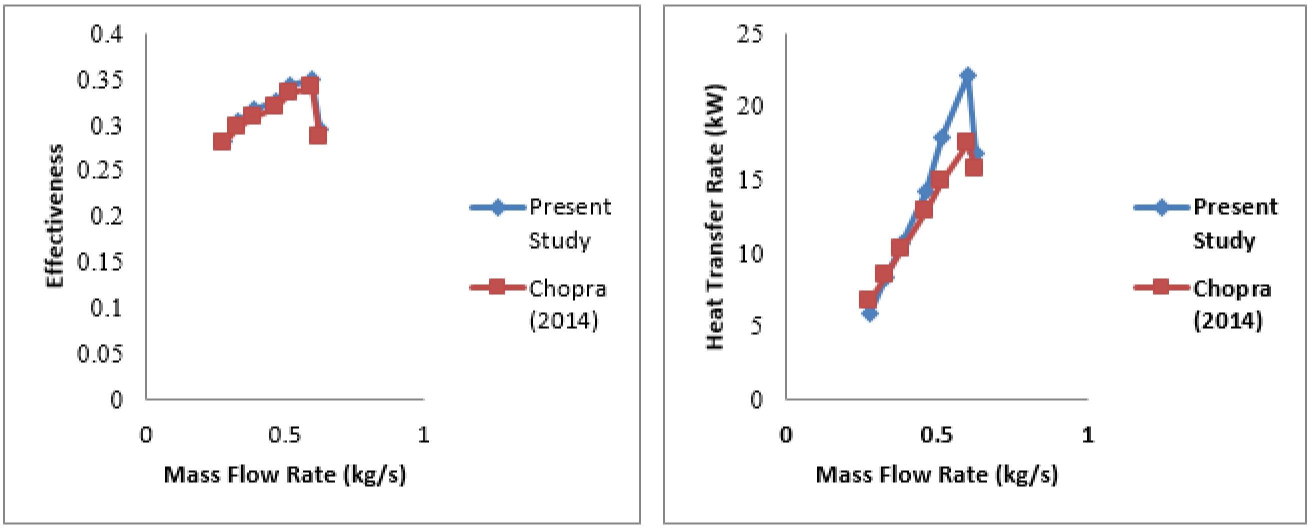


Figure. 3 Variation of heat exchanger effectiveness and heat transfer rate with mass flow rate

3.2 Effectiveness and heat transfer rate of different Fluids across Flow Configurations

Table 3. shows thermal performance behavior display by different fluid for each flow arrangement across different flow configurations. For all the flow configuration considered in this study, methanol displays the best fluid thermal performance among other fluids tested in terms of effectiveness. It can also be noticed that among the flow configuration considered, cross flow and shell and tube (n=3) gave best thermal performance for Ammonia in terms of heat transfer rate. This behavior indicates that both the working fluid type and the type of heat exchanger flow configuration influence the system thermal performance.

Table 3. Effect of flow arrangement on fluids type thermal performance in the system

Flow arrangement	Fluid Effectiveness and Heat transfer rate(kW)											
	Methanol		Ammonia		Air		Water		Engine oil		Glycerin	
	ε	*Q*	ε	*Q*	ε	*Q*	ε	*Q*	ε	*Q*	ε	*Q*
Parallel flow	0.71	27.8	0.32	22.3	0.33	20.7	0.34	21.0	0.53	27.2	0.50	26.5
Counter flow	0.78	33.8	0.33	23.6	0.35	22.9	0.36	23.3	0.57	31.6	0.53	30.2
Cross flow	0.76	31.7	0.57	71.4	0.34	21.9	0.35	22.2	0.55	29.6	0.52	28.7
Shell and tube(n=1)	0.74	30.5	0.32	22.9	0.34	21.8	0.35	22.1	0.55	29.3	0.51	28.0
Shell and tube(n=2)	0.92	46.8	0.51	57.5	0.52	50.0	0.53	50.7	0.76	56.6	0.73	56.8
Shell and tube(n=3)	0.98	52.6	0.57	88.7	0.56	72.9	0.64	73.9	0.87	73.3	0.84	75.0

3.3 Variation of effectiveness of different Fluids across Flow Configurations

Figure 4 shows the variation of different fluid type effectiveness with different flow configuration, it’s obvious that all the fluid types performed better in counter flow configuration except for the case of shell and tube configuration where the number of shell is more than one. This is because, under the same operating condition, more heat is transferred in counter flow arrangement due to uniform temperature difference in accordance to opposite direction of fluid flow. And also, for the case of shell and tube configuration, increase in the number of shell results into heat transfer area increase; causing greater temperature change to occur in fluids, thereby improving the effectiveness of the system. As shown in Figure. 5, it's evident that the counter flow configuration has the highest effectiveness except for the cases of cross flow and shell and tube with number of shell more than one across the entire fluid types considered. It's also evident that methanol has the highest effectiveness in all the flow configurations considered, as compared with other fluid types. This is due to the fact that methanol has a very high heat of vaporization and octane numbers in comparison to other fluids considered in this work. Thus, it can be inferred that different fluids have different capacity of effectiveness as regards the different flow configuration in the design of heat exchanger.

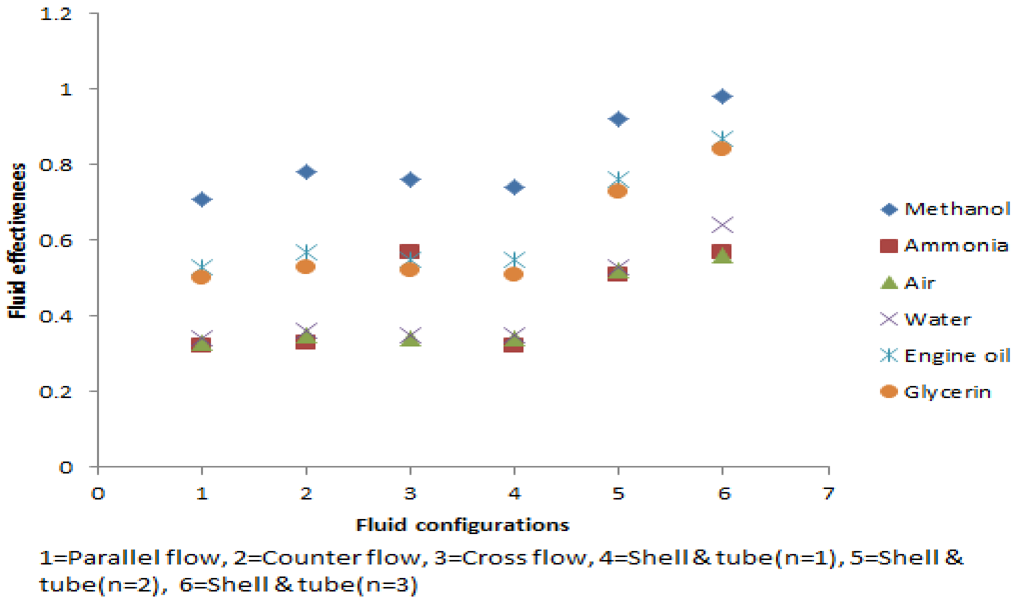


Figure. 4 Variation of fluid type effectiveness with different flow configurations

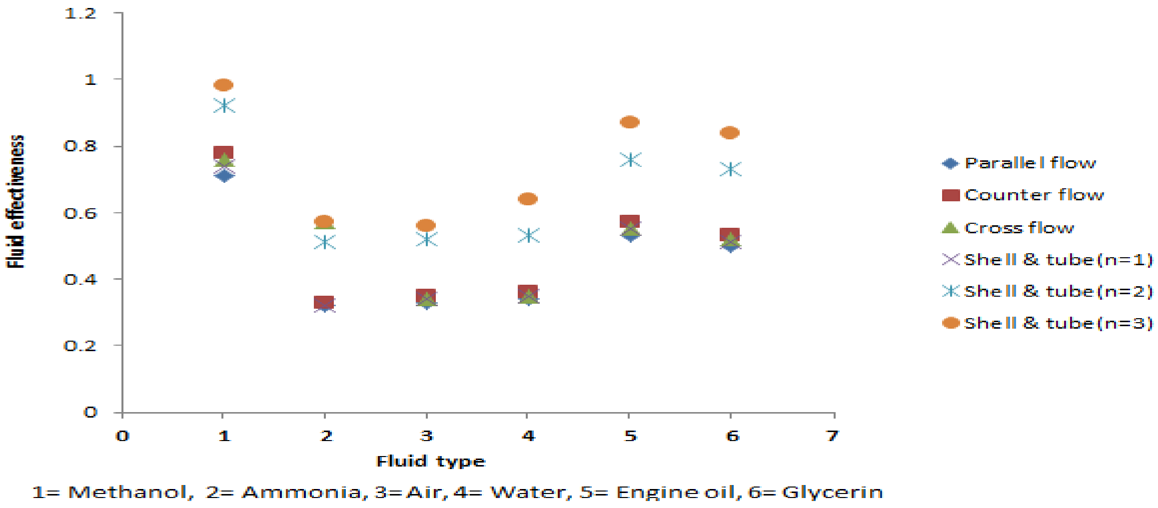


Figure 5 Variation of flow configuration effectiveness with different fluid types

3.4 Effect of Mass Flow Rate on Effectiveness of heat Exchangers

Table 4 also shows the effect of mass flow rate of fluids on the effectiveness of heat exchanger base on different flow configuration. The letter 'n' use in the table indicates the number of shell in Shell and Tube configuration. As expected and independently of the flow configuration considered in this study, the heat exchanger effectiveness increases with increasing mass flow rate of the system. This is similar to the behavior of effectiveness performance in the work of [4]. it can also be notice that the counter flow configuration has a better effectiveness performance as compared to other flow configuration under the same operating condition. However, with increase in the number of shell, shell and tube heat exchangers reflect higher effectiveness, as compared with other flow configuration under the same operating condition. This is due to the fact

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that increase in the number of shell results into heat transfer area increase; causing greater temperature change to occur in fluids, thereby improving the effectiveness of the system. Therefore, to achieve better thermal system effectiveness where the bulkiness of the heat exchanger design, as regards the number of shell and tube, is unproductive due to high cost of production and less compactness of the system, the counter flow configuration can be design for.

Table 4: Effect of mass flow rate of fluid on the effectiveness of heat exchanger system

Mass Flow Rate (kg/s)	Overall Heat Transfer coefficient (W/m^2)	Effectiveness					
		Parallel Flow	Counter Flow	Cross Flow	Shell and Tube		
					n=1	n=2	n=3
0.279	30.0	0.28	0.29	0.28	0.28	0.45	0.57
0.333	41.1	0.30	0.31	0.31	0.30	0.48	0.60
0.386	51.9	0.31	0.32	0.32	0.32	0.49	0.61
0.466	68.2	0.32	0.33	0.33	0.33	0.51	0.62
0.519	84.5	0.33	0.35	0.34	0.34	0.52	0.63
0.599	104.9	0.34	0.36	0.35	0.35	0.53	0.64
0.626	87.2	0.29	0.30	0.30	0.29	0.46	0.57

3.5 Variation of Heat transfer rate of different Fluids across Flow Configurations

Figure. 6 shows the variation of different fluid type's heat transfer rate with different flow configuration. It was observed that ammonia presents the best thermal performance with the highest value of 88.7kW followed by 75.06kW of glycerin. It is also noticed that ammonia has a better performance in cross flow configuration, shell and tube flow configuration in a condition where the number of shell is more than one under the same operating condition. This behavior is due to the fact that, ammonia has a low heat of vaporization which means that the intermolecular force of attraction between ammonia molecules is weak as reported by [11] and it also exhibit high melting point and lesser boiling point which indicates a low heat capacity compared to other fluids leading to its high heat transfer rate behavior observed in this study. Similarly, From Figure. 7, under the same operating condition among other flow configuration, it can also be seen that ammonia depicts best thermal performance in cross flow configuration. Similar behavior is observed for the case of shell and tube heat exchanger type where number of shell is 3. Generally, all the flow configurations considered in this study are better in all exceptional cases and can actually be designed for in other to achieve better thermal system effectiveness and heat transfer rate for healthy and better performance of heat exchanger system. It can be concluded that methanol and ammonia may act as a better substitute to the green offensive refrigerants commonly used in refrigeration system. This will enhance heat dissipating capacity of the heat exchanger system and consequently improve thermal performance of the system thus helping to solve the ozone depletion potential (ODP) and global warming potential (GWP) problems regarding environmental issues.

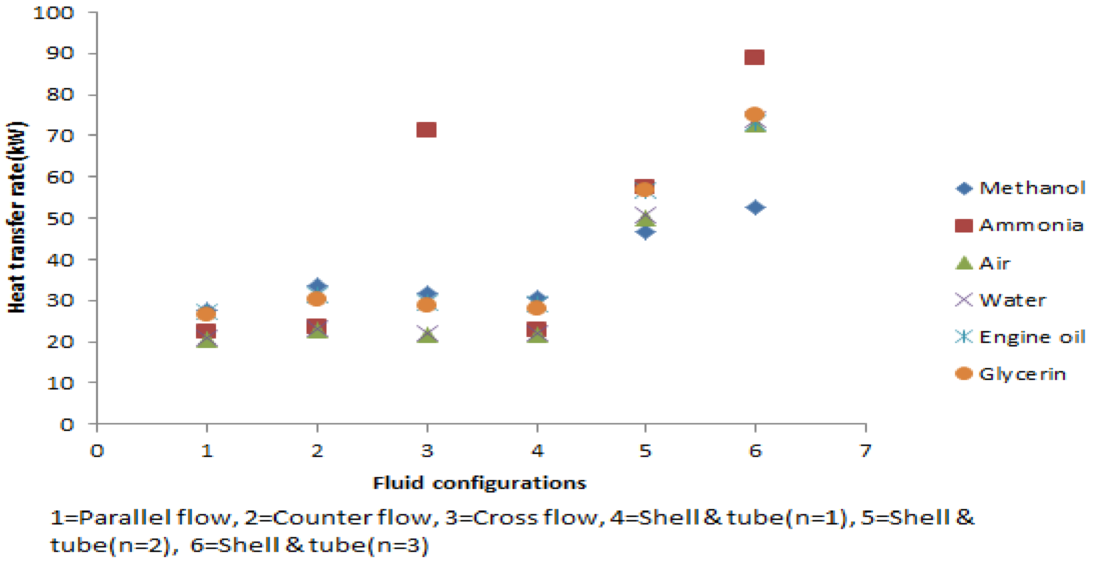

Figure. 6 Variation of fluid types heat transfer rate with different flow configurations

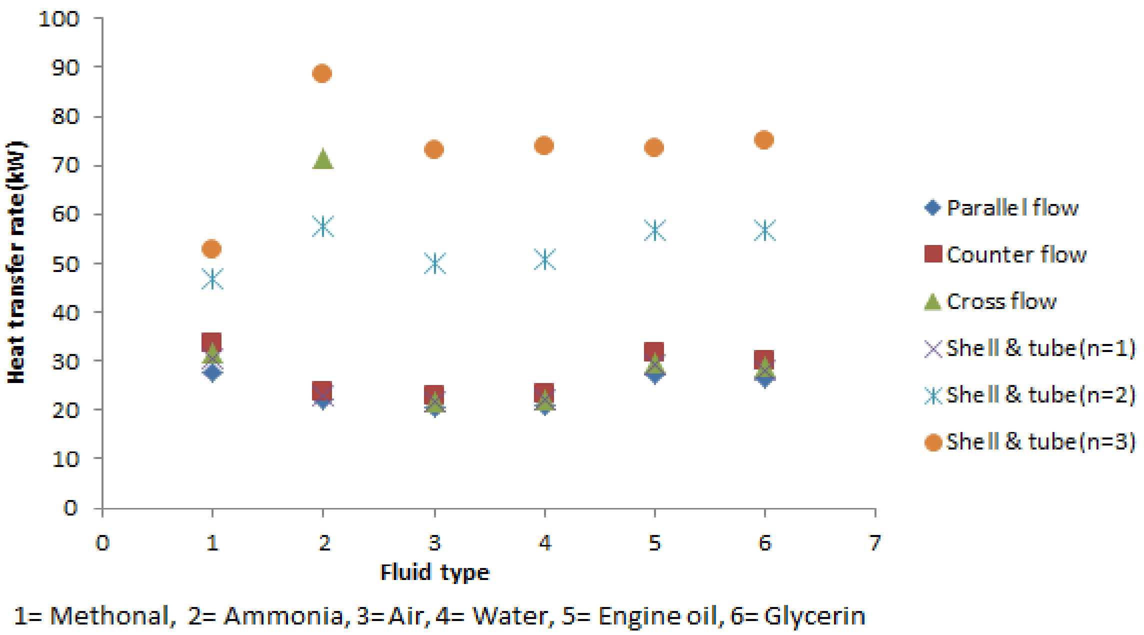

Figure. 7 Variation of flow configuration heat transfer rate across different fluid types

4. CONCLUSSION

Numerical analysis of developed software for different heat exchanger flow configurations was carried out in other to determine the variation of the effectiveness and heat transfer rate of different fluid types with the flow configurations. From the present study, the following conclusions can be draw:

1. In all the flow configuration considered in the study, effectiveness increases with increase in mass flow rate, the counter flow configuration has a better effectiveness, with the value of 1.036 to 1.059 times of that obtained from the parallel flow, cross flow and shell and tube at n=1 while the parallel flow heat exchanger has lower effectiveness as compared to other flow configuration under the same operating condition.
2. Methanol displays the best fluid properties in term of effectiveness and NTU followed by engine oil for the entire flow configuration considered in this work.
3. In term of heat transfer rate, ammonia presents the best thermal performance with the highest value of 88.7kW followed by 75.06kW of glycerin.
4. The results obtained from the numerical analyses were in good agreement with the experiments data obtained from literature with the discrepancies of the heat transfer rate and effectiveness estimated to be less than 11.63% and 1.55% respectively.

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