Investigation of Parallel Flow Heat Exchanger Response to Step Increase in its Heat Load

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Abstract: -

An experimental and theoretical analysis was conducted for simulation of open circuit parallel flow heat exchanger response to power increase transient in its heat load. Proper mathematical model is prepared to cover the heat transfer mechanism between the hot water in the primary circuit and the cold water in the secondary circuit during transient course. The model takes under consideration the effect of water heat up in the primary circuit due to step increase of its heat load added to same circuit on the physical and thermal properties linked to the parameters that are used for calculation of heat transfer coefficients on both sides of their tubes. Proper Math-Lab computer program was prepared for calculation the steady and transient states. The calculations covered all the variables that affect such type of transient mechanisms. The nominal power of the heat exchanger of 618w is subjected to step power increase transient of 880 w. The effect of the power increase percentage in the primary circuit on the average temperature buildup of the water in same circuit was investigated. The results covered the effect of power increase percentage of 130% of its nominal value during steady state for different secondary flow rates (120liter/hr, 170liter/hr and 200 liter/hr). The elapsed time required for the primary circuit average temperature to reach a steady state value was also calculated for different primary and secondary water flow rates. These calculations were supported with experimental measurements conducted on a standard parallel flow heat exchanger apparatus. The experimental results were compared with the theoretical results at fixed primary and secondary flow rates which showed reliable agreement with a maximum deviation of 4.2%. The results proved that water average temperature build up in the primary circuit has sharp tendency during the early stage of the transient course and then it reached to its saturation value after around 8-10 minutes.

Keywords: open circuit heat exchanger, heat load transient, parallel flow, response time

1. Introduction

Heat exchangers are widely used in the power generation systems, chemical process industries and other engineering systems used for heat exchange. One of the most commonly used type is shell and tube arrangement with either counter or parallel flow and with either the hot or cold fluid occupying the annular space and the other fluid occupying the inside of the inner pipe type of them. One fluid flows in the inside of the tubes, while the other fluid is forced through the shell and over the outside of the tubes to insure that the shell side fluid will flow across the tubes and thus induce higher heat transfer. In the relevant study the cross heat exchanger used water in both their primary and secondary circuits.

In general, heat exchangers are fairly easy to control, and except where very close control is needed, simplified methods of dynamic analysis give answers that are accurate enough for the practicing engineer. The approach taken here is to present exact transferred functions for a few of simpler cases in order to show the parameters that determine the lags and to explain the resonance effects sometimes found with distributed systems. During power increase transient, If the safety system related to the heat source device failed to shut down the heat source, the operator can shutdown it manually when he realize that there is an abnormal condition in the system, i.e insufficient cooling, by monitoring the different signals and indications in the control room. During such type of transient water temperature in the primary circuit will rises up until heat source device is shutdown. Then, this temperature starts to decrease after heat source device shutdown.

In case if the power source is kept at its value by mistake, water temperature in the primary circuit will continue its increase till it reaches the final steady state value at which the heat balance between heat added to the primary circuit by the heat source and that is removed by the secondary cooling circuit is equalized. The maximum increase in these temperatures above the normal operational values depends on the time lag between the initiation of power increase transient and the heat source device shutdown.

A review of literature on the transient response of single-pass parallel, counter and cross-flow heat exchangers with a step change in the inlet temperature is presented. Different predicting schemes were evaluated for their suitable range of operation and specific recommendations made regarding their suitability to types of problems. Most available solutions to date derived by analytical means and as a result to final solutions were very complex to utilize, [3]. However, several graphical representations of their solutions for specific values of independent variables matched those of a certain application are presented. The graphs could be used to determine transient response, [5] and [7]. A new technique using thermal network representation is found. This technique was employed to generate results for counter flow heat exchangers and presented them in a tabular from over a wide range of parameters. The results were valid for a step change in the minimum heat capacity rate side fluid inlet temperature. Transient thermal performance of counter flow heat exchangers has been modeled as a thermal net-work consisting of thermal capacitances at the nodes and thermal resistances. The network analyzed using a finite difference solution technique on a commercially available thermal network solver THERMONET – TransHX. The model incorporates the effect of wall and fluid thermal capacitance, fluid capacity rates, the size of the heat exchanger, and other operating parameters for a step change in the inlet temperature of one fluid stream, [10]. The current model and the solution technique are validated with the numerical results available. Tables are presented for non- dimensional time versus individual stream effectiveness over a wide range of capacity rate, number of transfer units, and wall capacitance ratio for the case of a counter flow heat exchanger undergoing a transient due to a step change, [5], [6] and [9].

Transient temperature field in a parallel flow heat exchanger numerically assuming fully developed hydrodynamic conditions is calculated. This approach uses fewer assumptions than published analytical studies. It shows the influence of physical and operational characteristics on experimentally defined parameters that describe the transient response of heat exchangers, [1].

The transient performance of a direct transfer, single pass cross flow heat exchanger with finite core capacity is investigated. The temperature response of the fluid streams as well as the separator plate has been obtained solving the conservation equations by finite difference formulation for step, ramp as well as exponential variation of the hot fluid inlet temperature and step and ramp variation in flow rates. The analysis has been done for the generalized case of unmixed fluid streams and finite capacitance of fluids and metal wall. Results are presented for step and ramp change in flow rate of hot and cold fluids, and step, ramp, exponential and sinusoidal variation in hot fluid inlet temperature. The mathematical model based in the study is reviewed for understanding different behaviors of the output parameters with respect to input functions despite the difference between the studied heat exchanger from that used in the relevant study.

In the relevant study the heat exchanger used water in both their primary and secondary circuits. The attempt of this study is to simulate the response of the primary circuit temperature build up according to the reduction or completely loss of secondary circuit flow during the failure of the safety systems to mitigate such type of transients. Such type of transients plays an important role in the evaluation of heat generation system safety and integrity specially, those related to nuclear reactors in which self control is a dominant factor due to the effect of negative temperature factor on the reactivity of the reactor core, [8].

An experimental and theoretical analysis was conducted for simulation of open circuit parallel heat exchanger dynamics during flow reduction transient in their secondary loops. Finite difference mathematical model was prepared to cover the heat transfer mechanism between the hot water in the primary circuit and the cold water in the secondary circuit during transient course. The model took under consideration the effect of water heat up in the secondary circuit due to step reduction of its flow on the physical and thermal properties linked to the parameters that are used for calculation of heat transfer coefficients on both sides of their tubes. The experimental results were compared with the theoretical results for certain power density value at different flow reduction percentages which show a reliable agreement.

The results proved that water average temperature build up in the primary circuit has sharp tendency when the percentage of flow reduction in the secondary circuit reach 25% of its nominal values, [2].

Theoretical Analysis

The test rig consists of shell type parallel flow heat exchanger. The hot water flows in shell side, primary side, while the cold water flows in tubes, secondary side. The secondary side consists of 4 tubes. Thermal conductivity of the copper tubes, k=349 W/m.˚C. The outer radius of the tubes, ro = 8 mm, the inner radius of the tubes, ri =7 mm. The total heat exchange area Ah= 67380 mm. Shell diameter = 50 mm. Heat exchanger length = 355 mm. Heat transfer coefficient for both inner surface and surface of tube bundles could be calculated using proper analytical and empirical formulas. This procedure could be conducted for the inner surface and then repeated for the outer surface. The formulas adopted for calculating heat transfer coefficient in our case are recommended by the supplier company for the type of the heat exchanger selected for experimental work, [4]. Heat transfer coefficient in the shell side, secondary circuit is calculated based on the following equations:

$$Nu = 1.86.[Re.Pr.(d/L)]^{0.33} . (\mu/\mu_w)^{0.14} \quad \dots (1)$$

The equation is applicable for the following range of input parameters: Re.Pr.(d/L) > 10 , L/d>2 , 100<Re< 2100 , 0.48< Pr <16700

Where:

μ is the dynamic viscosity at average temperature.

μ_w is the dynamic viscosity at wall temperature.

The following equations could be used for the turbulent flow in the tube side, primary circuit to simulate such case, [11].

$$Nu = 0.036\, Re^{0.8}.Pr^{0.33}.(d/L)^{0.125} \quad \ldots(2)$$

With:

$10 < (L/d) < 400$, $Re > 10000$, $0.7 < Pr < 16700$.

The thermal and physical properties of the water flowing in both primary and secondary circuits are obtained by interpolation among their values listed in specified tables.

Interpolation is conducted at mean water temperature between input and output values for each of primary and secondary circuits.

$$T_m = (T_{inlet} + T_{outlet})/ 2 \quad \ldots (3)$$

Here we assume the following:

1. The secondary circuit is open loop i.e. the inlet temperature of the water in the circuit is constant.
2. The heat source (power input) is constant during transient period and this source is continuous during the transient course of secondary flow reduction..
3. The average water temperature in the secondary side of the heat exchanger is calculated based on the temperature difference across the secondary side of the heat exchanger.
4. Total mass of water in the primary circuit is (M). Then balance between the heat added to this amount of water by electrical heater and the heat rejected to the secondary circuit could be represented by the following equation:

$$M{*}Cp_p * \frac{d\theta p_a}{dt} = Qi - [\ (\theta p_a - \theta s_a){*}(Uo{*}Ao)\ ] \quad \ldots(4)$$

$$\theta s_a = Ts_i + \frac{Qi}{2*(m^{\bullet} * Cps)} \quad \ldots(5)$$

$$M{*}Cp_p \frac{d\theta p_a}{dt} = [\ Qi - (\theta p_a - Ts_i - \frac{Qi}{2*(m^{\bullet} * Cps)}){*}(Uo{*}Ao)\ ] \quad \ldots(6)$$

$$M{*}Cp_p \frac{d\theta p_a}{dt} = Qi - \theta p_a * Uo{*}Ao + Ts_i * Uo{*}Ao + \frac{Qi{*}Uo{*}Ao}{2*(m^{\bullet} * Cps)} \quad \ldots(7)$$

$$M{*}Cp_p \frac{d\theta p_a}{dt} + \theta p_a * Uo{*}Ao = Qi + Ts_i * Uo{*}Ao + \frac{Qi{*}Uo{*}Ao}{2*(m^{\bullet} * Cps)} \quad \ldots(8)$$

$$\frac{M{*}Cp_p}{Uo{*}Ao} * \frac{d\theta p_a}{dt} + \theta p_a = \frac{Qi}{Uo{*}Ao} + \frac{Qi}{2*(m^{\bullet} * Cps)} + Ts_i \quad \ldots(9)$$

Substitute for:

$$C_r = \frac{(M{*}Cp)_p}{Uo{*}Ao} \quad \ldots(10)$$

$$C_s = m^{\bullet} * Cps \quad \ldots(11)$$

$$C_r \frac{d\theta p_a}{dt} + \theta p_a = Q_i \left(\frac{1}{Uo*Ao} + \frac{1}{2*m^{\bullet}*Cps} \right) + Ts_i \qquad ...(12)$$

Let: $\theta p'_a = \theta p_a - Ts_i$ ... (13)

Then $\frac{d\theta p'_a}{dt} = \frac{d\theta p_a}{dt}$ ... (14)

Substitute in eq (9):

$$C_r \frac{d\theta p'_a}{dt} + \theta p'_a = Q_i \left(\frac{1}{Uo*Ao} + \frac{1}{2*m^{\bullet}*Cps} \right) \qquad ...(15)$$

Using Laplace transformation and assume the following:

$\tau = C_r$ ...(16)

$k = \frac{1}{Uo*Ao} + \frac{1}{2\,C_s}$ ...(17)

Then $(1 + \tau_s)\,\theta p'_a = k\,Q_i$ ...(18)

$\theta p'_a = k\,Q_i\,(1 - e^{-t/\tau})$ ...(19)

As $t \longrightarrow \infty$

$\theta p'_a = k\,Q_i$ ...(20)

$\theta p_a = Ts_i + \left(\frac{1}{Uo*Ao} + \frac{1}{2\,C_s}\right) Q_i$..(21)

$Tp_o = 2\,\theta p_a - Tp_i$ ...(22)

$Tp_o = 2\left[Ts_i + \left(\frac{1}{Uo*Ao} + \frac{1}{2\,C_s}\right) Q_i \right] - Tp_i$ ...(23)

$Tp_o = 2Ts_i + \left(\frac{2}{Uo*Ao} + \frac{1}{C_s}\right) Q_i - Tp_i$ ...(24)

Base steady state value on t = 1.5 min, Using the following input values:

$Q_i = 618$ w $\qquad Q_h = 100$ lt/hr

$Q_c = 170$ lt/hr

$Ts_i = 24.4$ °C

$Ts_o = 28.3$ °C

$$A_o = 4\,\pi\,d_o\,L$$
$$= 4\,\pi\,(1.6 * 10^{-3} * 0.335)$$
$$= 0.0674\ m^2$$

$C_s = \frac{170}{3600} * 4170 = 197$ W/°C

$Tp_o = 33.5$ °C

$Tp_i = 39$ °C

Then, $U_o = 893$ W/m^2.°C

Based on steady state condition parameters the transient state is studied and their parameters are evaluated. Using equation (18) the average primary circuit coolant temperature (θp_a) as the end of the transient course is calculated for step input in thermal load of

$\Delta Q = 800$ watt

$\theta p_a = 24.4 + \left(\frac{1}{893*0.0674} + \frac{1}{2*198}\right) * 1418$

$= 48.3^\circ C$

Using equations (10) & (16) the following equation is derived

$$\theta p = Ts_i + k\, Q_i\, (1 - e^{-t/\tau}) \quad \ldots(25)$$

Where:

$$K = \frac{1}{Uo*Ao} + \frac{1}{2\, C_s} = \frac{1}{893*0.0674} + \frac{1}{2*170} \quad \ldots(26)$$

$$= 0.0191$$

Where:

$$\tau = C_r = \frac{(M*Cp)_p}{Uo*Ao} \quad \ldots(27)$$

Where: $(M * Cp)_p = Cp_w\, M_w$

$$= 4170 * 1.2$$

$$= 5004\ J/^\circ C$$

$$\tau = \frac{5004}{893*0.0674} = 83.14\ sec$$

At t=60 sec

$$\theta p = 24.4 + 0.0191 * 1418 * (1 - e^{-60/83.1})$$

$$= 38.3^\circ C$$

At t=120 sec

$$\theta p = 24 + 0.0191 * 1418 * (1 - e^{-120/83.1})$$

$$= 45^\circ C$$

Hand written computer program is prepared for calculations of the steady state and transient values of water average temperature in the primary and secondary circuits. The structure of the program allows easy interpolation among the values of the physical properties based on the values of water temperature in both circuits. The empirical formulas adapted for the recent case study could be easily adapted for investigating cases that covers other type of heat exchangers.

2. Experimental Work

The test rig consists of shell type cross flow heat exchanger. Water in both shell and tube sides are circulated by two pumps of maximum flow rate of 300 l/hr for each one. Water volumetric flow rate in both shell and tube sides are measured using proper calibrated flow meter Water added and drained from both sides using proper isolation valves. Heat addition to the primary circuit is ensured by electrical heater that is adjusted by proper resistances from 0-1600 Watt. The hot water flows in shell side, primary side, while the cold water flows in tubes, secondary side. **Fig.1** and **Plate.1** shows the main components of the test rig. After cross checking all the mechanical and electrical connections, the circulation pumps in both sides are put on to circulate the water inside the circuits. Water flow rate in the primary circuit is fixed at 100 liter/hr, while water flow rate in secondary circuit is fixed at 170 liters/hr using the proper valves. The electrical heaters are turned on to heat up the water in the primary circuit to its operational steady state values. The steady state heat input of 618W is controlled using the specified knobs. The measured temperatures at different points within primary and secondary sides reaches to their steady state values, which are considered as those temperatures at time equals zero for the transient condition. Upon subjecting the primary side to 800W step change, the temperature at different points in both primary and secondary sides are measured versus time using stop watch till they reach their steady state values. The response of the primary circuit temperature versus time is repeated using secondary flow rate of 200 liter/hr while water flow rate in the primary side is kept at its nominal value of 100 liter/hr.

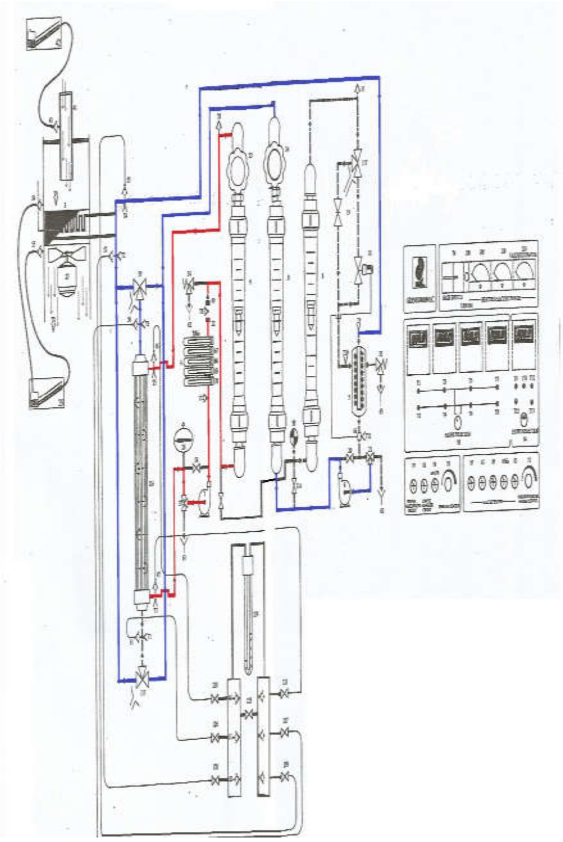

Fig.1 Test rig layout.

Plate.1 Test rig used for conduction the experiments.

3. Results and Discussion

All the results and graphs are based on constant water inlet temperature to the secondary circuit equals 25^{o}C and constant water flow rate in the primary circuit equals 190 liter/ hr. **Tables (1-5)** illustrate all the experimental and theoretical results related to average primary temperature versus time and the constant times governed with transient conditions.

Table.1 Experimental & Theoretical average water temperature in the primary & secondary circuits after step change in the heat load = 800watt, based on Q_c =170 liter/hr, Q_h = 100 liter/hr.

Time, min	Experimental results						Theoretical results
	Temperature across primary side, ^{o}C		Temperature across secondary side, ^{o}C		Primary circuit average temperature, θp, ^{o}C	Secondary circuit average temperature, θs, ^{o}C	Primary circuit average temperature, θp, ^{o}C
	T5,in	T7,out	T3,in	T1,out	-	-	-
0 min	39.1	33.5	24.4	28.3	36.3	26.35	36.6
1 min	44.9	36.2	24.4	29.4	42.5	26.35	38.3
2 min	47.1	37.8	24.5	29.9	44.5	26.9	45
3 min	49.6	39.4	24.5	30.5	45.8	27.2	48.4
4 min	51.2	40.4	24.5	30.8	46.9	27.5	50
5 min	52.5	41.2	24.5	31.2	47.8	27.65	50.8
6 min	53.6	41.9	24.5	31.4	48.5	27.85	51.1
7 min	54.4	42.5	24.5	31.6	49	27.95	51.3
8 min	55.2	42.8	24.5	31.8	49.4	28.05	51.4
9 min	55.6	43.2	24.5	31.9	49.6	28.15	51.4
10 min	55.8	43.4	24.6	32	49.9	28.2	51.5
11 min	56.2	43.6	24.6	32.1	50.1	28.3	51.5
12 min	56.4	43.7	24.6	32.2	50.2	28.35	51.5
13 min	56.6	43.8	24.6	32.2	50.3	28.4	51.5
14 min	56.7	43.8	24.6	32.2	50.4	28.4	51.5
15 min	56.8	43.9	24.6	32.2	50.4	28.4	51.5

Table.2 Experimental & Theoretical average water temperature in the primary circuit after step change in the heat load = 800watt, based on Q_c =200 liter/hr, Q_h = 100 liter/hr

Time, min	Experimental results						Theoretical results
	Temperature across primary side, ^{o}C		Temperature across secondary side, ^{o}C		Primary circuit average temperature, θp, ^{o}C	Secondary circuit average temperature, θs, ^{o}C	Primary circuit average temperature, θp, ^{o}C
	T5,in	T7,out	T3,in	T1,out	-	-	-
0 min	38	32.5	24.1	27.6	35.25	25.85	35.25
1 min	38.3	32.6	24.1	27.7	38.6	25.9	38
2 min	39	35.3	24.1	28.1	41.2	26.1	44.6
3 min	40	38	24.1	28.5	43.3	26.3	47.9
4 min	44	39	24.1	29.2	44.8	26.6	49.5
5 min	48	39.6	24.1	29.9	46.2	27	50.2
6 min	52.2	40.2	24.1	30.6	46.8	27.3	50.5
7 min	53	40.6	24.1	30.7	47.4	27.4	50.7
8 min	53.8	41	24.1	30.8	47.75	27.45	50.8
9 min	54.2	41.3	24.2	30.9	48	27.55	50.8
10 min	54.5	41.5	24.2	31	48.3	27.6	50.9
11 min	54.8	41.7	24.2	31.1	48.5	27.65	50.9
12 min	55	41.9	24.2	31.2	48.61	27.7	50.9
13 min	55.2	42	24.2	31.2	48.7	27.7	50.9
14 min	55.3	42.1	24.2	31.2	48.8	27.7	50.9
15 min	55.4	42.2	24.3	31.3	48.85	27.75	50.9

Table.3 Theoretical average water temperature in the primary circuit after step change in the heat load = 800watt, based on different water flow rates in the secondary circuit, Q_h = 100 liter/hr

Time, min	Q_s = 120 liter/min	Q_s = 170 liter/min	Q_s = 200 liter/min
0 min	40.3	36.6	35.25
1 min	41.9	38.3	38
2 min	50.3	45	44.6
3 min	54.6	48.4	47.9
4 min	56.7	50	49.5
5 min	57.6	50.8	50.2
6 min	57.9	51.1	50.5
7 min	58.2	51.3	50.7
8 min	58.3	51.4	50.8
9 min	58.3	51.4	50.8
10 min	58.5	51.5	50.9
11 min	58.5	51.5	50.9
12 min	58.5	51.5	50.9
13 min	58.5	51.5	50.9
14 min	58.5	51.5	50.9
15 min	58.5	51.5	50.9

Table.4 Normalized time constant versus Primary flow reduction percentages

Primary flow reduction, (%)	h_{i2}/h_{i1}	U_2/U_1	τ_2/τ_1
0.25	0.33	0.5	2
0.33	0.41	0.58	1.72
0.5	0.57	0.73	1.37
0.75	0.79	0.88	1.14

Table.5 Normalized time constant versus secondary flow reduction percentages

Primary flow reduction, (%)	h_{i2}/h_{i1}	U_2/U_1	τ_2/τ_1
0.25	0.63	0.77	1.3
0.33	0.69	0.82	1.22
0.5	0.79	0.88	1.14
0.75	0.91	0.95	1.05

Figs.2&3 show the experimental and theoretical relationships between the water average temperature buildup in the primary circuit versus time during power supply increase from (618W to 1418W) at different water flow rates of (170 liters/hr and 200 liters/hr in the secondary circuit) and water flow rate of (100 liters/hr in the primary circuit). The graphs show reliable coincidence between the experimental and theoretical results. The theoretical part of both graphs show certain delay in the average primary water temperature response within first 120 seconds in comparison to the experimental results as the time constant, τ should take under consideration the effect of mass and heat capacity of all structural material in addition to the water contained in the system.

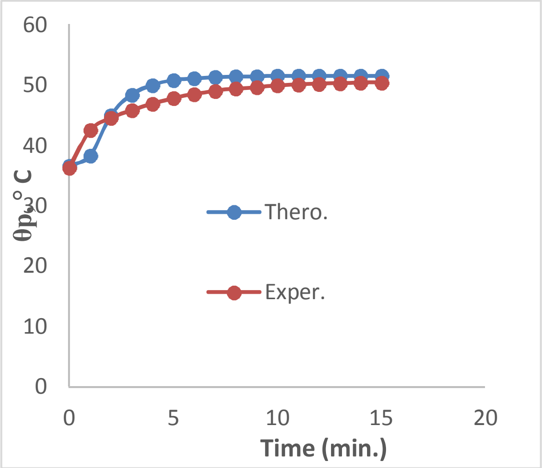

Fig.2 Experimental & Theoretical average water temperature, Tpa buildup in the primary circuit versus time during power supply increase from (618W to 1418W) based on secondary flow rate of 170 l/h.

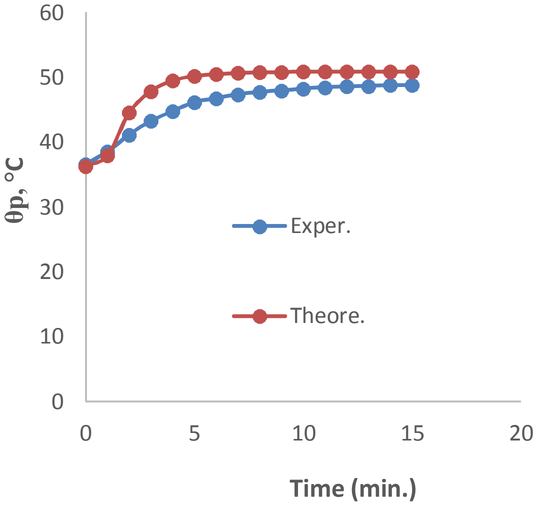

Fig.3 Experimental & Theoretical average water temperature, Tpa buildup in the primary circuit versus time during power supply increase from (618W to 1418W) based on secondary flow rate of 200 l/h.

Fig.4 shows theoretical relationship between the average temperature build up in the primary circuit versus time during power supply increase from (618W to 1418W) at different secondary flow rates, 120 liters/hr, 170 liters/hr and 200 liters/hr and water flow rate of 100 liters/hr in the primary circuit. It is clear that the steady state values of the water average temperature buildup are inversely proportional to water flow rate in the secondary circuit.

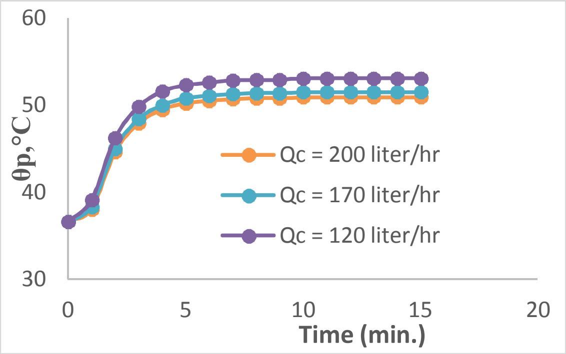

Fig.4 Theoretical average water temperature, Tpa buildup in the primary circuit versus time during power supply increase from (618W to 1418W) based on different secondary flow rates.

Fig.5 shows the relationship between normalized water average temperatures in the primary the end of power increase transient with respect to its nominal value versus water flow rates in the secondary circuit at constant water flow rate in the primary circuit. The results clarify that these steady state values at the end of each transient course is inversely proportional to secondary circuit water flow rate and that the normalized average water temperature increase with respect to its nominal value decreases from 45.1% at water flow rate of 120 liter per hour to 38.4% at water flow rate of 250 liter per hour.

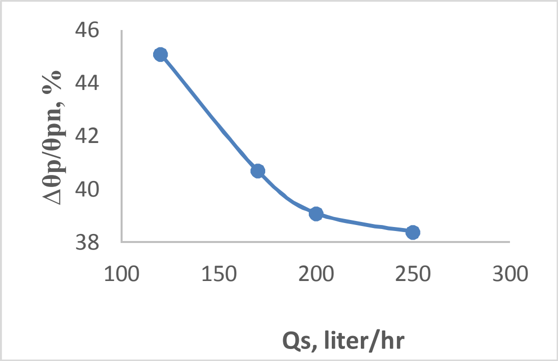

Fig.5 Theoretical results for the normalized water temperature increase at the end of transient course with reference to its value during steady state operation versus secondary flow rate at 130% of power density input to the primary circuit.

Fig.6 and Fig.7 and the **tables (4,5)** show the relationship between normalized time constant with respect to its nominal value versus normalized water flow rate reduction in the primary circuit and secondary circuits respectively with respect to their nominal values. Both graphs demonstrate that the time constant related to the transient behavior of the average water temperature in the primary circuit with respect to power increase disturbance is inversely proportional with water flow rates in both circuits. However, the flow rate in the primary circuit is more effective in comparison to that in the secondary circuit as the normalized values of these parameters are 2 and 1.3 respectively.

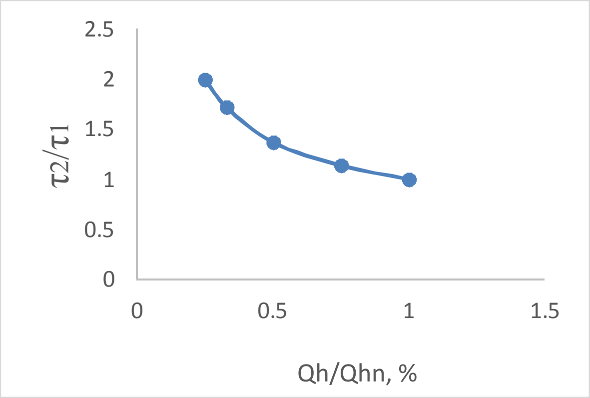

Fig.6 Theoretical results for the normalized time constant with respect to its nominal value versus normalized water flow rate reduction in the primary circuit with respect to its nominal value.

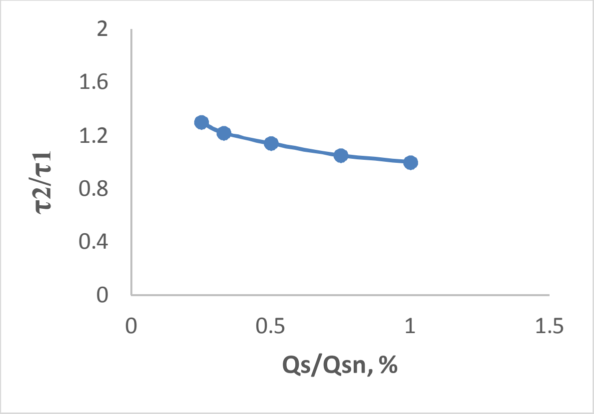

Fig.7 Theoretical results for the normalized time constant with respect to its nominal value versus normalized water flow rate reduction in the secondary circuit with respect to its nominal value.

4. Conclusions

Investigation of heat exchangers transient conditions based on step increase in the heat load added to its primary circuit during operation is very important in the design of safety engineering feature systems related to any power production or chemical process industries. The results obtained from this study proved reliable modeling for power increase transient based on the coincidence between the results obtained from both experimental and theoretical analysis. It is clear that the steady state values of the water average temperature buildup are inversely proportional to water flow rate in the secondary circuit. From other hand this study gives an indication to the estimated mission time required for the operation of safety systems based on the elapsed time of each transient course to avoid heat generation systems from approaching the boiling crisis accompanied by the poor heat transfer mechanisms. The results showed that the time constant related to the transient behavior of the average water temperature in the primary circuit with respect to power increase disturbance is inversely proportional with water flow rates in both circuits.

5. Nomenclature

M: Water mass in the primary side, kg

Cp_p: Water heat capacity in the primary circuit, J/kg.°C.

Cp_s: Water heat capacity in the secondary circuit, J/kg.°C.

θp_a: Water average temperature in the primary circuit, °C.

θs_a: Water average temperature in the secondary circuit, °C.

Q_i: Heat input to the primary circuit, w.

U: Heat transfer coefficient between primary and secondary circuit, w/m^2.^{o}C.

A_o: Heat exchange area between primary and secondary circuits, m^2.

$m^\bullet$: Water mass flow rate in the secondary circuit, kg/s.

L: Secondary pipe length, m.

d: Secondary pipe diameter, m.

t: Time, s.

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استجابة مبادل حراري ذو الجريان الموازي لزيادة خطوة عابرة في الحمل الحراري

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الخلاصة:

تم إجراء تحليل تجريبي ونظري لمحاكاة الاستجابة لزيادة القدرة العابرة في الحمل الحراري في مبادل حراري من نوع الدائرة المفتوحة والجريان الموازي. تم إعداد نموذج رياضي لتغطية آلية نقل الحرارة بين الماء الساخن في الدائرة الابتدائية والماء البارد في الدائرة الثانوية أثناء الحالة العابرة. يأخذ النموذج في الاعتبار تأثير حرارة الماء في الدائرة الأولية بسبب زيادة درجية في الحمل الحراري المضاف إلى نفس الدائرة على الخصائص الفيزيائية والحرارية المرتبطة لحساب معاملات نقل الحرارة على جانبي أنابيب المبادل الحراري. تم إعداد برنامج حاسوب Math-Lab مناسب للحسابات المتعلقة بالحالة الثابتة والعابرة. وتغطي الحسابات جميع المتغيرات التي تؤثر على هذا النوع من الآليات العابرة. حيث تم تعريض قدرة المجهز الحراري ذو 680 واط الى زيادة خطوة بالقدرة قدرها 800 واط. تم دراسة تأثير نسبة زيادة الطاقة في الدائرة الابتدائية على متوسط تراكم درجة حرارة الماء في نفس الدائرة. شملت النتائج تأثير زيادة الطاقة بنسبة 130٪ من قيمتها الطبيعية في الحالة المستقرة خلال معدل تدفق ماء في الدائرة الثانوية بقيمة (120 لتر/ساعة, 170لتر/ساعة و200 لتر/ساعة).كما تم حساب الوقت المنقضي المطلوب لدرجة حرارة الدائرة الأولية للوصول إلى قيمة الحالة مستقرة لمعدلات جريان ماء مختلفة في الدائرة الأبتدائية والدائرة الثانوية. وأيدت هذه الحسابات مع القياسات التجريبية التي أجريت على مبادل حراري من نوع الدائرة المفتوحة والجريان الموازي. وتمت مقارنة النتائج التجريبية مع النتائج النظرية في معدلات التدفق الأولية والثانوية الثابتة التي أظهرت اتفاقا موثوقا به وبأنحراف أعظم قدره 4.2%. وأظهرت النتائج أن متوسط درجة حرارة الماء المتراكم في الدائرة الابتدائية له ميل حاد خلال المرحلة المبكرة من الدورة العابرة ثم وصل إلى قيمة التشبع بعد حوالي 8-10 دقائق.

الكلمات المفتاحية: مبادل حراري من نوع الدائرة المفتوحة، الحمل الحراري العابر، الجريان الموازي، زمن الاستجابة