PROJECT REPORT

LIQUID PHASE HEAT TRANSFER IN HELICAL COILED HEAT EXCHANGER

UNIVERSITY OF PUNE

B. E. CHEMICAL

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ABSTRACT

This project is related to heat transfer in Helical Coil Heat Exchanger, in which, forced convection takes place in the tube while, natural convection takes place in the hot fluid bath, due to density difference. Cooling water is passed through the coil, while the liquid bath is supplied with heat, by electric immersion rod.

For this purpose an experimental setup is built up for determining the,

- Overall Heat Transfer coefficient
- Inside Heat Transfer Coefficient of helical coil.
- Total Time require for Cooling of Batch for helical coil, immersed in hot liquid bath.

Following graphical conclusion is done:

1. Overall Heat Transfer Coefficient v/s Cooling water flow rate
2. Inside heat transfer coefficient of coil v/s cooling water flow rate
3. Temp in helical coil v/s tube length

Further more, batch cooling process is done along with its simulation, with help of mathematical model, for the entire system.

The complete procedure is done for liquid bath of

1. water
2. 3% soap solution
3. 1.5% Starch solution.

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1
INTRODUCTION

Helical coiled heat exchanger is widely used in Chemical Process Industries. There application is mainly in controlling the temperature of the reactors for exothermic reactions, in cryogenics and also in other heat transfer applications.

1.1 HEAT TRANSFER COEFFICIENT

As in literature (5,6) in case of convective heat transfer taking place from surface to fluid, circulating current dies out in the immediate vicinity of the surface and film of fluid, free of turbulence, covers the surface. Through this film heat transfer takes place by thermal conduction and as thermal conductivity of most fluids is low, the main resistance lies there. Therefore increase in velocity of fluid over the surface results in improved heat transfer mainly because of reduction in thickness of film. The equation for rate of heat transfer by convection under steady state is given by,

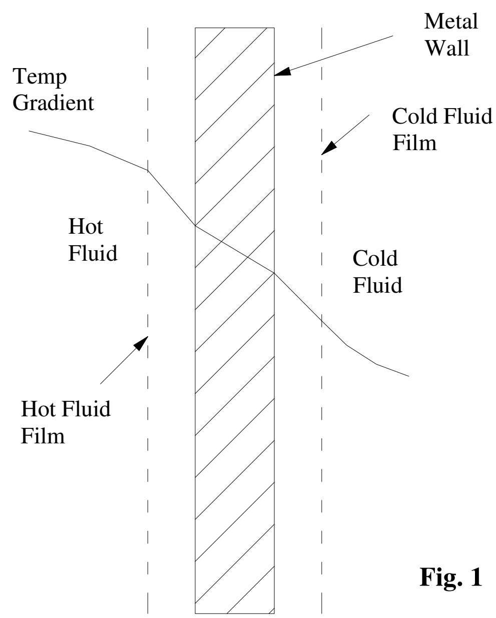


Fig. 1

$$Q = h\ A\ \Delta T$$

Where 'h' is the film coefficient or surface coefficient. The value of 'h' depends upon the properties of fluid within the film region, hence it is called

'Heat Transfer Coefficient'. It depends on various properties of fluid, linear dimensions of surface and fluid velocity (i.e. nature of flow).

Numerically, Heat Transfer Coefficient (h) is the quantity of heat transferred in unit time through unit area at a temperature difference of one degree between the surface and the surrounding. Its SI unit is ($W/m^2.K$). The term 1/h is the thermal resistance.

The 'overall Heat Transfer Coefficient' can be in terms of thermal resistances. The summation of individual resistances is the total thermal resistance and its inverse is the overall HTC, U. That is,

$$\frac{1}{U} = \frac{1}{h_o} + \frac{A_o}{A_i} \quad \frac{1}{h_i} + R_{fo} + \frac{A_o}{A_i} R_{fi} + R_w$$

Where,

U = overall heat transfer coefficient based on outside area of tube wall

A = area of tube wall

h = convective heat transfer coefficient

R_f = thermal resistance due to fouling

R_w = thermal resistance due to wall conduction

and suffixes 'i' and 'o' refer to the inner and outer tubes, respectively

Due to existence of superimposed secondary flow, the heat transfer rates (& the fluid pressure drop) are higher in curved tube than in an equivalent straight tube at the same flow rate and the transfer mechanisms are also more complicated.

1.2 PROJECT JUSTIFICATION

Due to lack of experimental data available regarding liquid behavior in helical coils and also in case of heat transfer data, which is not the case in Shell & Tube Heat exchanger, problems regarding design are always occurring. So to best of our effort and help from the staff members, experiment was carried out in lab itself to determine various data regarding heat transfer and fluid flow pattern in helical coiled heat exchanger.

The objective of the project is to obtain a better and more quantitative insight into the heat transfer process that occurs when a fluid flows in a helically coiled tube.

The sensible heat transfer to liquids flowing in helically coiled tubes was experimentally evaluated. The study covered the fluid flow range extending from laminar flow through transition to high turbulent flow. Experimental data was gathered for three different liquids in liquid bath and by passing water through the inside of helical tubes.

1.3 APPLICATIONS [2, 7]

Use of helical coils for heat transfer applications:

1. Helical coils are used for transferring heat in chemical reactors and agitated vessels because heat transfer coefficients are higher in helical coils. This is especially important when chemical reactions have high heats of reaction are carried out and the heat generated (or consumed) has to be transferred rapidly to maintain the temperature of the reaction. Also, because helical coils have a compact configuration, more heat transfer surface can be provided per unit of space than by the use of straight tubes.

2. Because of the compact configuration of helical coils, they can be readily used in heat transfer application with space limitations, for example, in steam generations in marine and industrial applications.
3. The helically coiled tube is eminently suited for studying the characteristics of a plug flow reactor in reaction kinetic studies because the secondary motion present in the helical coil destroys the radial concentration gradient.
4. The existence of self induce radial acceleration field in helical coils makes helical coils most desirable for heat transfer and fluid flow applications in the absence of gravity field, such as for space ships in outer space.
5. Helical coiled tubes have been and are used extensively in cryogenic industry for the liquefaction of gases.

2
LITERATURE SURVEY

G. S. Aravind et al. (1) reported in their paper the study of heat transfer for coolant in helical coil. In this study, water, 3% soap and Carboxy methyl cellulose (CMC) solutions are used as bath liquids. Effect of these liquids on the natural convection taking place between hot bath and coolant was studied. Overall heat transfer coefficient (U) and nusselt numbers for various fluid flows were determined and compared for all the bath liquids.

It was determined that U and Nusselt no. were both high for water as bath liquid for almost all the flow rates.

Following equations are used:

The overall heat transfer is calculated as heat transfer obtained as under:

$$Q = m\, Cp\, \Delta T$$

Where, 'm' is mass flow rate of coolant, Cp the heat capacity of water

$$\Delta T = T_o - T_i$$

The overall heat transfer coefficient (U) is calculated using the following equation:

$$U = Q / A\, (T_b - T_m)$$

The coil side heat transfer coefficient (h_i) is calculated from the following equation,

$$h_i = Q / (A\, \Delta T_m)$$

where ΔTm is difference between the average wall temperature & the mean temperature of the circulating water.

Singh et al. (2) reported in his thesis the experimental study of heat transfer with distilled water & Dowtherm G flow through helically coiled tubes. A Reynold's No. range from 6 to 46000 was investigated for two helically coils 9.99 & 20.64 inches diameter (Type seamless stainless steel). For both helically coiled tubes, an axial length of 10 feet was heated electrically by passing DC current through tube wall.

Various relations were obtained by performing the above experiment like,

1. Fanning friction factor v/s Reynold's no.
2. Nusselt no. v/s Peripheral location

K. R. Arora (4) in his literature has explained the nature of fluid flow in curved pipes. A complete explanation on, formation of secondary fluid flow in curved pipes and how this secondary flow completely destroys the formation of boundary layer (which provides resistance to heat transfer) is given.

T. R. Brown (3) reported the equations and computer program in this article which provide the means for determining the relationship between time, batch temperature, rate of heat transfer and flow rate or outlet temperature of heat transfer medium in batch heating or cooling. The mathematical equations used for the modeling are,

$$\theta = \frac{B\ C_b}{W\ C_w} \left(\frac{1}{1 - e^{-UA/WCw}} \right) \ln \left(\frac{T_{b1} - T_{w1}}{T_b - T_{w1}} \right)$$

$$q = B\ C_b\ K\ (T_{b1} - T_{w1})\ e^{-K\theta}$$

$$K = \frac{W\ C_w}{B\ C_b} \left(1 - e^{-UA/WCw} \right)$$

$$Tw = \frac{Q}{W\ C_w} + T_{w1}$$

By understanding how these variables relate to each other, we can reduce design errors & oversight, overly expensive design & poor startups.

3
THEORY OF HELICAL COILS

Stirred tanks can be provided with either (or both) an external jacket or internal coil for heat transfer. A full helical coil is commonly used giving maximum surface area, but requires a two piece vessel.

3.1 FLUID FLOW IN CURVED PIPES [2]

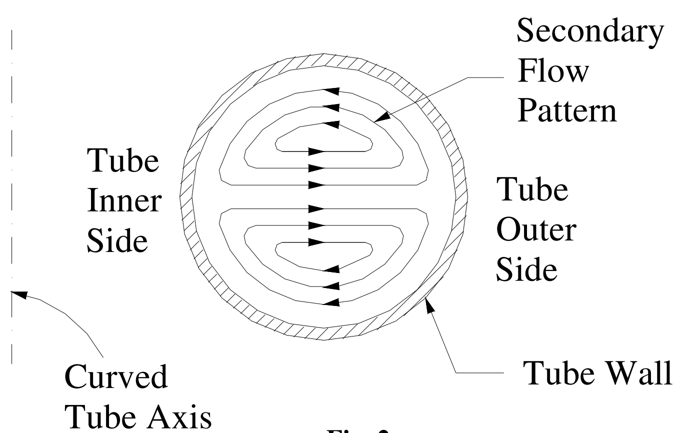


Fig. 2

When a fluid flows through a straight tube, the fluid velocity is maximum at the tube center, zero at the tube wall & symmetrically distributed about the axis. However, when the fluid flows through a curved tube, the primary velocity profile indicated above is distorted by the addition of secondary flow pattern. The secondary flow is generated by centrifugal action and acts in a plane perpendicular to the primary flow.

Since the velocity is maximum at the center, the fluid at the center is subjected to the maximum centrifugal action, which pushes the fluid towards the outer wall. The fluid at the outer wall moves in ward along the tube wall to replace the fluid ejected outwards. This results in the formation of two vortices symmetrical about a horizontal plane through the tube center. Figure no.(2) is a sketch of secondary flow pattern.

3.2 ACTUAL THEORY [4]

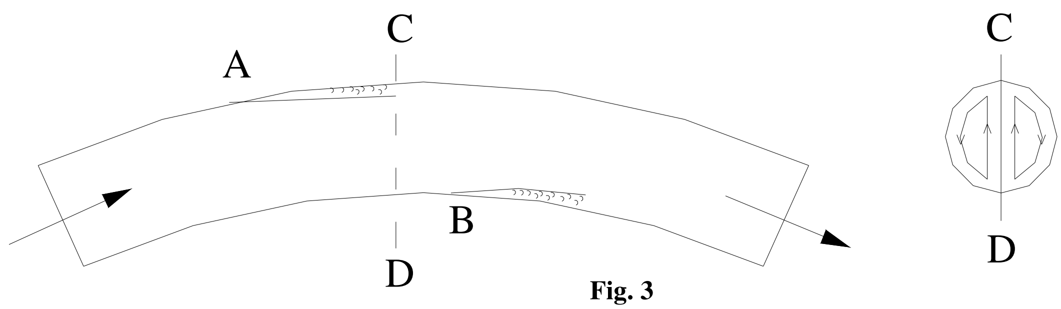


Fig. 3

In radial direction a pressure gradient is developed to create an acceleration, which acts towards the center of the bend. The pressure at the outside of the pipe is more than the pressure at the inner side. The increased pressure at the outside causes the velocity of the particle to decrease. This creates eddies. Separation takes place at the outer wall. Separation and eddies also occur at point B on the inside of the bend, due to the inertia of the water. More over, the pressure which is very low at D increases as the point B approaches & adverse pressure exists.

If radial section CD is taken across the bend, a secondary flow as shown in the figure no.(3) is found to exist. Along the horizontal diameter CD, the pressure increases with the radial distance. But the pressure decreases as the low pressure region near the wall is approached. The difference in the pressure causes an outward motion along the wall form C to D. to satisfy the continuity condition, there is a flow from D to C along the radial direction. Thus a secondary flow is developed. This flow is in addition to the main flow which takes place along the axis of the pipe & a complex flow pattern occurs.

3.3 ADVANTAGES & DISADVANTAGES [6]

Advantages of coils

1. Coils give better heat transfer performance, since they have lower wall resistance & higher process side coefficient.
2. A coil can provide a large surface area in a relatively small reactor volume.
3. Coils are more versatile for scale – up.
4. Jacket heat transfer area rises as the 0.67 power of the vessel volume, it is much easier to instant coil area in proportion to volume (providing that the coils are not so densely packed as to interfere with the flow).

Disadvantages of coils

1. For highly reactive material or highly corrosive material coils cannot be used, instead jackets are used.
2. Cleaning of vessels with coils becomes much difficult than with jackets.
3. Coils play a major role in selection of agitation system. Densely packed coils can create unmixed regions by interfering with fluid flow.
4. Rheological complex materials are easier to process with jackets than with coils.

For coil Overall Heat Transfer Coefficient : 400 – 600 W / m^2 ^oK

Minimum velocity of liquid in coil : 1.5 m / sec

4
EXPERIMENTAL SETUP

DESCRIPTION OF INDIVIDUAL UNITS

4.1 HELICAL COIL

Helical coil of 285 mm in diameter was used. The coil was made from initial spiral, seamless copper tube of 7.5 mm ID & 9.4 mm OD. The axial length of helical coiled tube is 15m. Straight tube sections were provided at the inlet and the outlet of the coil. Dimensions of helical coil is given in table below.

Some flattening of the tube resulted during the formation of the helical coils. Experiments were performed with the axis of the coil in the vertical direction. The fluid entered the coil at the bottom and exited from the top.

Item	Dim
Coil diameter, tube – center – to – tube – center, (D_c), mm	285
Straight tube outside diameter, d_o, mm	9.4
Straight tube inside diameter, d_i, mm	7.5
Approximate number of turns in helical coil, nos.	16
Curvature ratio, d_i/D_c	0.0263
Axial & heated length of helical coil, m	14.5
Coil pitch, tube – center – to – tube – center, mm	19.4

4.2 FLUID BATH

Fluid bath is made in stainless steel vessel having diameter of 355 mm & the vessel has a capacity of 50 lit.

The bath is connected with 5000 Watt, immersion type electric heater. The bath is completely insulated with insulation ropes. The temperature of the fluid bath is measured with the help of Cr – Al (K – type) electrode.

4.3 PUMPS

A centrifugal pump was used to pump the fluid through the experimental loop. The pump was manufactured by Laxmi Pumps. The pump has rated capacity of 18 lpm of water and capable of developing head of 15 m.

4.4 AC POWER SOURCE

Equipment	Voltage	Ampere
For Heater	220	2
For Motor	220	2
For cooling tower	440	16

4.5 THERMOCOUPLES

Thermocouples used during the experiment was Chromel – Alumel (Cr – Al) (K – Type, range : $0^{o}C$ to $1500^{o}C$) along 12 – channel with temperature indicator supplied by Datacone Engineers, Sangli. The thermocouples were fully insulated with high temperature insulation beeds (Range up to $1200^{o}C$). Six thermocouples were connected on the outside of helical coil at specific distance from the inlet, one each in inlet and outlet of cooling coil and one in liquid bath in the vessel. All the thermocouples were connected to the temperature indicator which is calibrated for that particular thermocouple.

4.6 ROTAMETER

Rotameter, calibrated for readings up to 11 lpm is used. The rotameter is directly connected to the pump itself. The rotameter is supplied by Datacone Engineers.

4.7 COOLING TOWER

Cooling tower is supplied by Datacone Engineers, Sangli. The tower consists of meshed type of packing. The tower consists of both, forced type and induced type arrangement. The blower is used for forced draft and exhaust fan is used for induced draft.

The hot water is sprayed from the top in the tower and blower as well as fan is started for faster cooling.

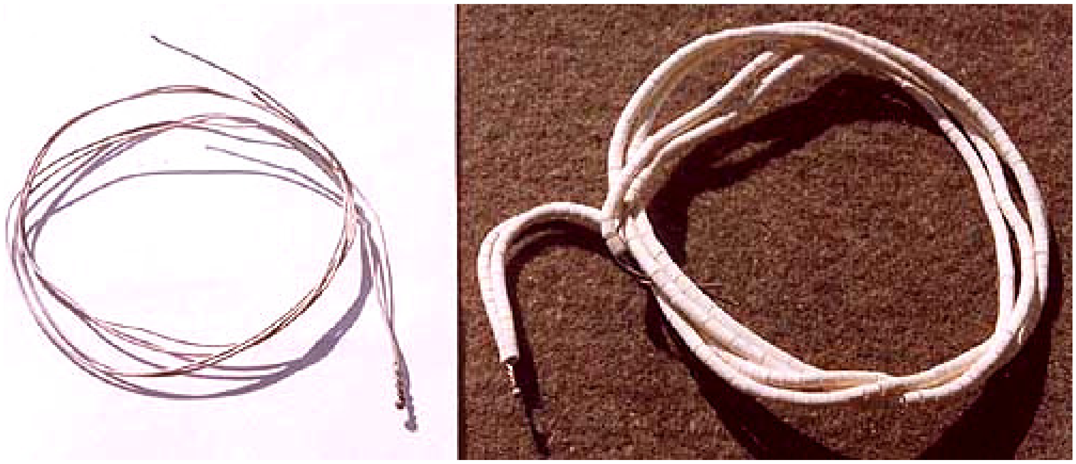


Fig. 4 Thermocouple with & without insulation

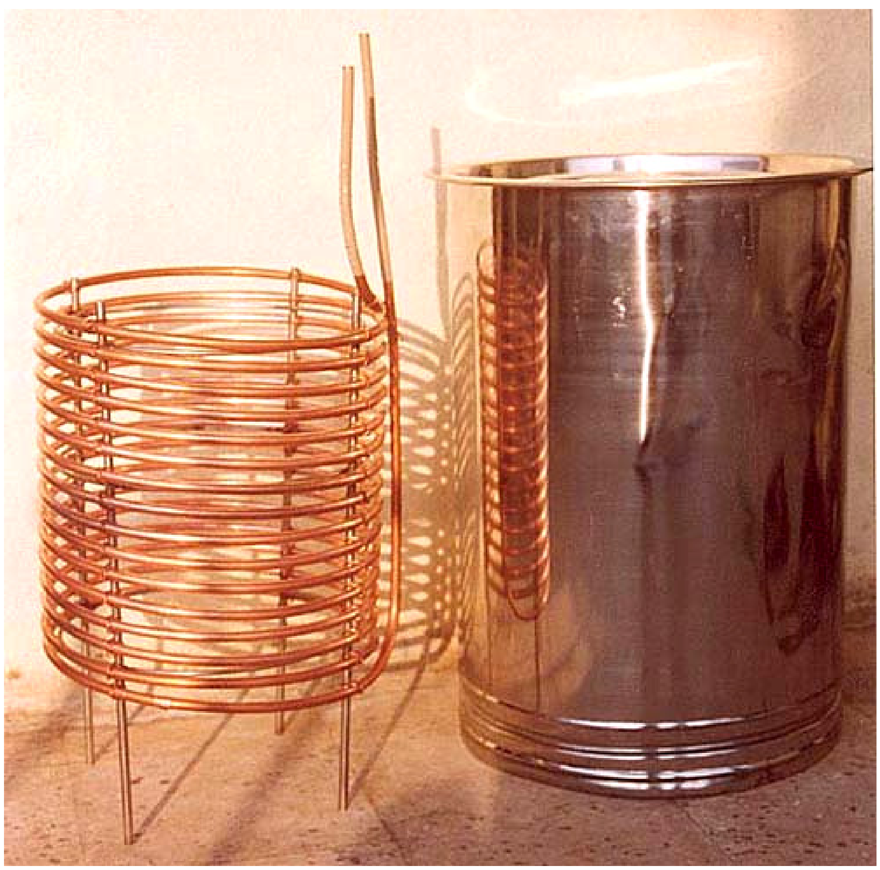


Fig. 5 Helical coil & 50 lit tank before installation

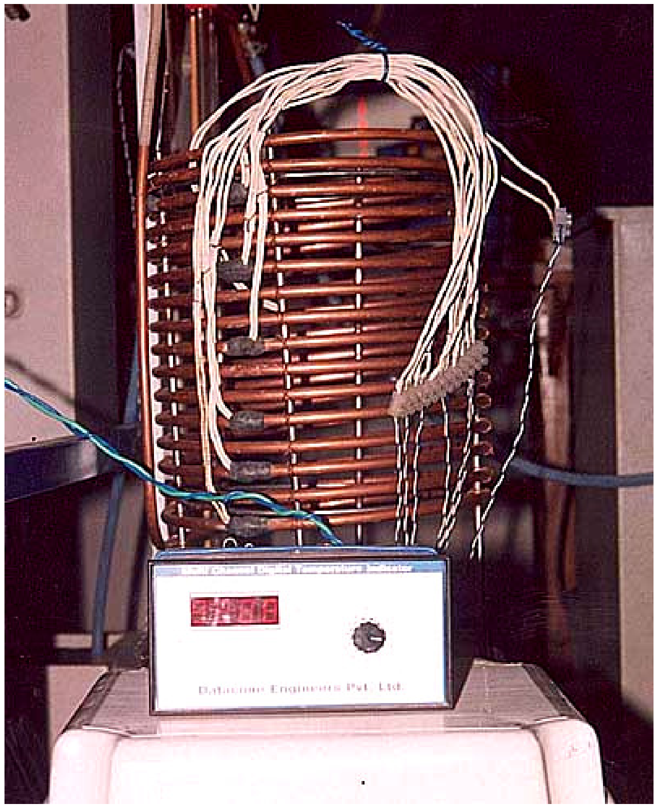


Fig. 6 Thermocouples attached to coil at specific distance & connected to Temp Indicator

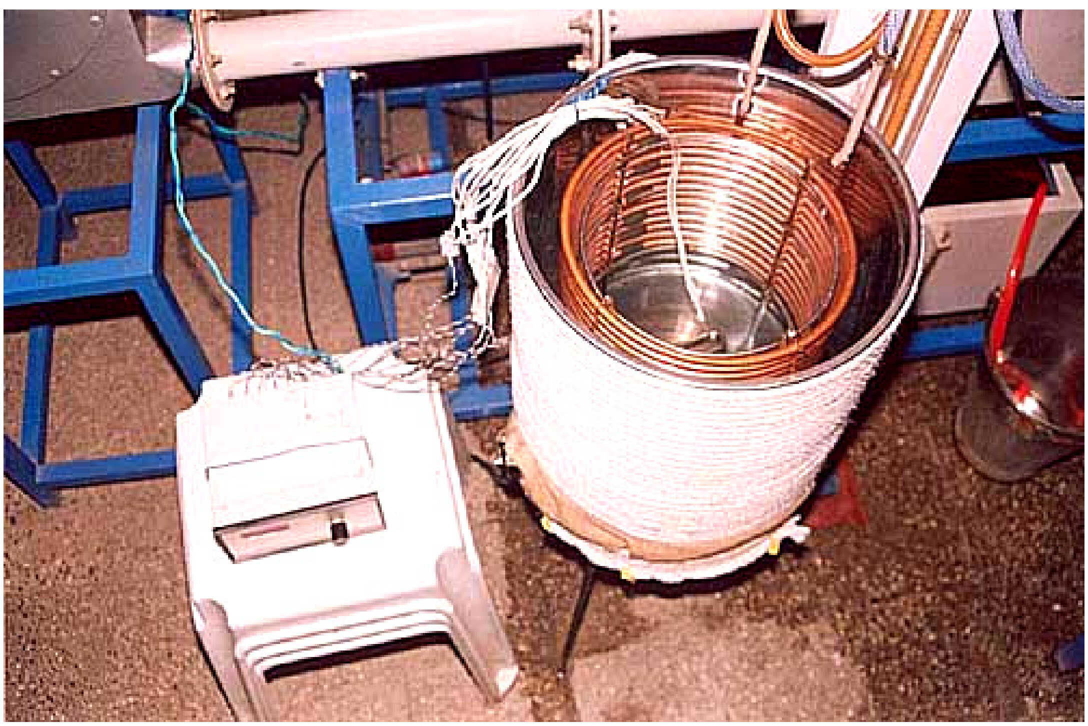


Fig. 7 Top view of the set – up

Fig. 8 The complete set – up in closed loop with cooling tower

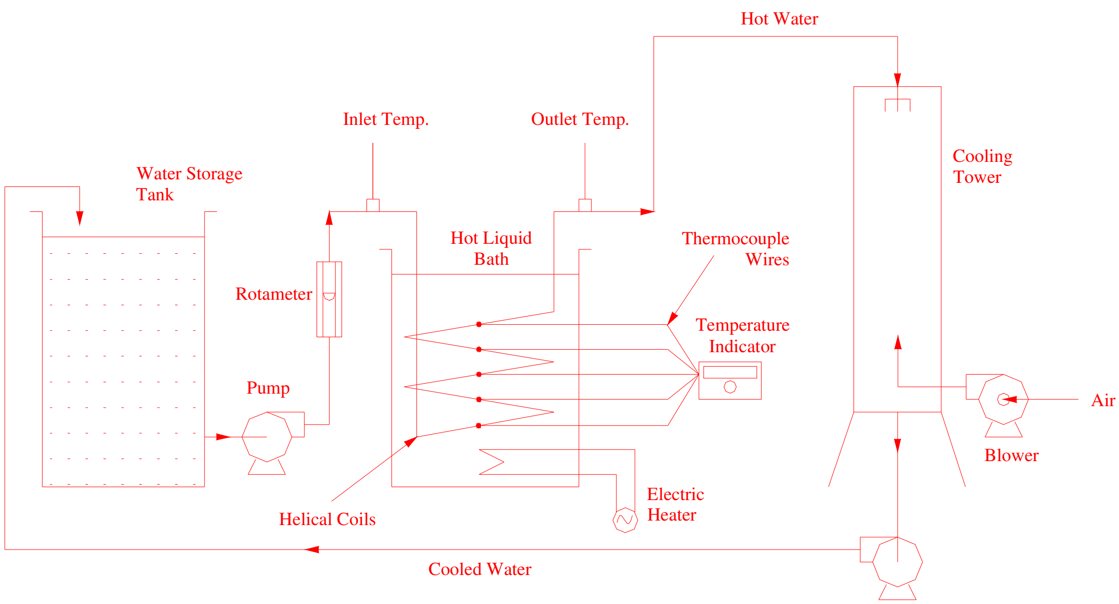


Fig. 9 Flowsheet of complete set up

5
EXPERIMENTAL PROCEDURE

5.1 START – UP PROCEDURE

The helical coil was installed in the fluid flow circuit. Six thermocouples were attached to the tube wall, one each for inlet and outlet flow rate and one for fluid bath temperature. The thermocouples were then connected to the temperature indicator, which was calibrated to specified thermocouple type. The fluid flow circuit was tested for possible leaks by flowing fluid at the anticipated maximum flow rate through the circuit. Any leaks were detected and eliminated. The vessel was completely insulated with jute bags and special insulation rope to minimize heat loss.

The start up procedure was followed every time the experimental setup was activated to gather experimental data. The start – up procedure consisted of following steps:

1. The heater in the fluid bath was activated to bring the fluid to desired operating temperature.
2. The temperature indicator was switched on to measure the bath & other temperatures.
3. The pump was started and the fluid was allowed to circulate through the circuit.
4. Cooling tower (Blower, Exhaust fan for creating forced & induced draft cooling) was switched 'on'.
5. The control valve was then adjusted according to the desired flow rate shown by the rotameter.

6. The pump in the cooling tower was then started to send the hot coolant from the collection vessel to the top of the cooling tower.

5.2 DATA GATHERING PROCEDURE

1. The fluid flow rate was adjusted to the desired value by means of flow control valve.
2. The cooling water flow rate to the cooling tower was adjusted so that the bath temperature would remain constant.
3. The experimental setup was operated for at least half an hour for the system to achieve steady state. The cooling water flow rate was checked regularly and adjusted.
4. After about half hour operation, the following experimental data was measured:
    a. The helical coil surface temperatures (indicated by the thermocouples cemented on the coil).
    b. The inlet an exit bulk fluid temperatures.
    c. The fluid flow rate indicated by the rotameter.
    d. The bath fluid temperature.
    e. The coil inlet and exit fluid pressure, as indicated by the manometer.

If steady state is not achieved then above steps are repeated again after an interval of half an hour.

The flow rate was changed to new sets of conditions and the entire data gathering procedure was repeated for new set of input conditions.

The water used for cooling coil was changed frequently to minimize the solids content.

5.3 DATA REDUCTION

Experimental data were gathered for helical coil using water as cooling media and hot liquid bath of water, 3% soap solution, 1.5% starch solution. In all 18 runs were made for all the batches with 6 runs per batch. The raw experimental data is given in table ahead. Computer programs were written to reduce the experimental data using the application made by using Microsoft Visual Basic 6.0. computer program and coding is given in detail ahead in report.

Data reduction consisted of the following steps:

1. Calculation of the overall heat balance.
2. Calculation of coil side Heat Transfer Coefficient and overall heat transfer coefficient.
3. Calculation of dimensionless numbers.

Calculation of Overall Heat Balance

The overall heat balance for each data run was calculated as follows:

Heat input rate, Q_{input} = 5000 watt

Heat output rate, $Q_{out} = m\ C_p\ (t_{out} - t_{in})$

Where,

m = mass flow rate of fluid flowing through the coil, gm/sec

C_p = specific heat of the fluid at the average bulk fluid temperature in the coil, J/gm.^{o}K

t_{out} = bulk fluid temperature at the coil exit, ^{o}k

t_{in} = bulk fluid temperature at the coil inlet, ^{o}k

The inlet and exit fluid flowing through the helical coil was measured by the Chromel – Alumel thermocouple.

Calculation of Local & Overall Heat Transfer Coefficient

The overall heat transfer coefficient is calculated using the following equation,

$$U = Q / A\ (T_b - T_m)$$

The coil side heat transfer coefficient is calculated by using this equation,

$$h_i = Q / (A\ \Delta T_m)$$

Where,

U = Overall Heat Transfer Coefficient, watt / (m^2 ^oK)

h_i = Coil side heat transfer coefficient, watt / (m^2 ^oK)

A = Total surface area of the coil, m^2

T_b = Bath temperature, ^oK

T_m = Mean temperature of coolant,[$(T_i + T_o) / 2$], ^oK

$T_{av} = (T_1 + T_2 + T_3 + T_4 + T_5 + T_6) / 6$

$\Delta T_m = T_{av} - T_m$

Calculations of relevant dimensionless numbers

Dimensionless Number	Symbol	Definition
Reynolds	Re	$\frac{(d_i)\ (G)}{\mu}$
Prandtl	Pr	$\frac{(Cp)\ (\mu)}{k}$
Nusselt	Nu	$\frac{(h)\ (d_i)}{(k)}$

Given ahead, are experimental readings for water, 3% soap and 1.5% starch solution for determining OHTC and inside HTC.

RUN NO: 1

Date: 23/02/2005

Initial temperature of liquid bath: 75°C

Liquid in bath: Water

Coolant: Water

Time for each steady state: 1 Hr

Flow rate (lpm)	Bath temp (°C)	Coolant Temp (°C)		Thermocouple Stationed on coil (°C)					
		Inlet	Outlet	T_1	T_2	T_3	T_4	T_5	T_6
1	66	32	62	47	52	56	59	62	63
2	56	30	52	41	44	46	48	51	52
3	54	30	49	39	42	43	45	47	49
4	52	30	46	38	40	41	43	45	46
5	50	30	43	37	38	39	40	41	42
6	48	30	41	36	37	38	39	39	40

RESULT FOR RUN NO: 1

Flow rate (gm/sec)	Q (watt)	Tavg for wall (°C)	T_m (°C)	U (W/m2°K)	h_i (W/m2°K)	N_{Re}	N_{Nu}
16.67	2092.662	56.5	47	322.542	645.084	3301.895	7.88
33.33	3069.24	47	41	599.21	1498.02	6603.79	18.29
50	3976.058	44.16	39.5	803.019	2495.09	9903.685	30.47
66.67	4464.346	42.16	38	933.183	3137.69	13207.58	38.32
83.33	4534.102	39.66	36.5	983.554	4425.99	16509.47	54.06
100	4603.857	38.16	35.5	1078.58	5055.55	19811.369	61.75

RUN NO: 2

Date: 24/02/2005

Initial temperature of liquid bath: 80°C

Liquid in bath: 3% soap solution

Coolant: Water

Time for each steady state: 1 Hr

Flow rate (lpm)	Bath temp (°C)	Coolant Temp (°C)		Thermocouple Stationed on coil (°C)					
		Inlet	Outlet	T_1	T_2	T_3	T_4	T_5	T_6
1	68	31	63	46	50	54	58	61	62
2	58	31	51	39	41	44	47	50	51
3	54	31	47	37	39	40	43	45	46
4	53	31	44	36	37	38	40	42	43
5	51	31	42	35	36	37	39	41	42
6	50	31	38	34	35	36	37	37	38

RESULT FOR RUN NO: 2

Flow rate (gm/sec)	Q (watt)	Tavg for wall (°C)	T_m (°C)	U ($W/m^{2o}K$)	h_i ($W/m^{2o}K$)	N_{Re}	N_{Nu}
16.67	2232.173	55.16	47	311.278	800.431	3301.895	9.77
33.33	2790.216	46.66	41	480.66	1441.95	6603.790	17.613
50	3348.260	41.66	39	653.685	3676.98	9905.685	44.914
66.67	3627.281	39.33	37.5	685.315	5794.03	13207.58	70.77
83.33	3836.548	38.33	36.5	774.843	6128.30	16509.74	74.857
100	4185.325	37.66	36	875.471	7353.96	19811.36	89.828

RUN NO: 3

Date: 5/03/2005

Initial temperature of liquid bath: 80°C

Liquid in bath: 1.5% starch solution

Coolant: Water

Time for each steady state: 1 Hr

Flow rate (lpm)	Bath temp (°C)	Coolant Temp (°C)		Thermocouple Stationed on coil (°C)					
		Inlet	Outlet	T_1	T_2	T_3	T_4	T_5	T_6
1	73	32	64	45	53	54	59	62	64
2	64	32	52	39	44	43	46	49	51
3	59	32	46	36	40	40	42	44	46
4	57	32	43	36	38	39	40	42	43
5	56	32	41	35	38	38	39	40	41
6	55	32	40	34	36	37	38	39	40

RESULT FOR RUN NO: 3

Flow rate (gm/sec)	Q (watt)	Tavg for wall (°C)	T_m (°C)	U ($W/m^{2o}K$)	h_i ($W/m^{2o}K$)	N_{Re}	N_{Nu}
16.67	2232.173	56.166	48	261.474	800.431	3301.895	9.777
33.33	2790.216	45.333	42	371.412	2451.32	6603.789	29.943
50	2929.72	41.333	39	428.981	3676.98	9905.685	44.914
66.67	3069.238	39.666	37.5	460.932	4148.39	13207.58	50.673
83.33	3138.993	38.5	36.5	471.407	4596.22	16509.74	56.143
100	3348.260	37.33	36	516.067	7353.96	19811.36	89.828

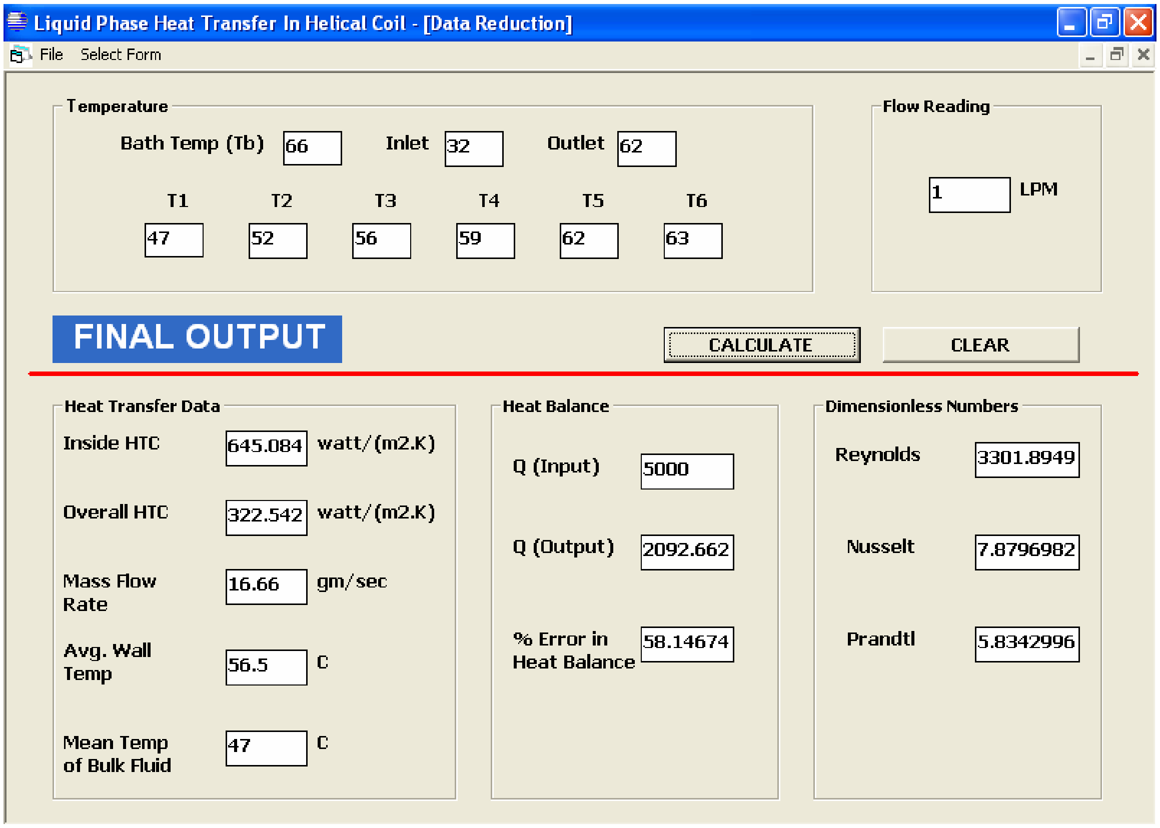


Fig. 10. GUI of program for calculations

Given above is Graphical User Interface (GUI) of program made using Microsoft Visual Basic 6.0. The calculations for all the 3 runs were made using this program. In the figure, above the red line is input while below it is the calculated output. The program coding has been given in chapter 7.

5.4 RESULTS & DISCUSSIONS

RATE OF HEAT TRANSFER IN HELICAL COIL

The graph below explains how the rate of heat transfer decreases as the coolant passes through the length of the coil.

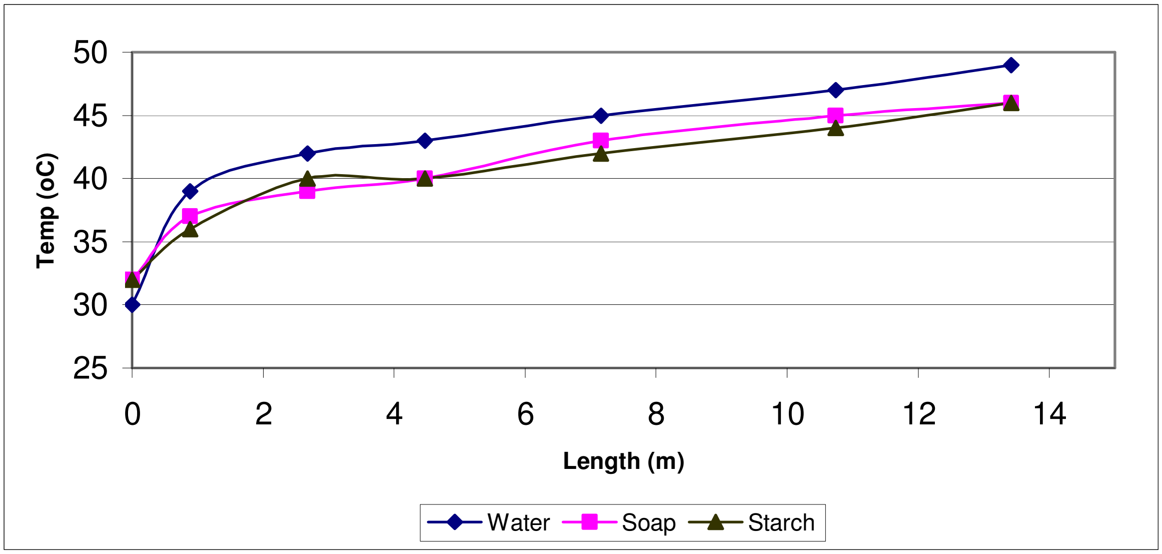


Fig. 11 Graph of Temp in coil v/s Length of coil

As seen in graph above, the rate of heat transfer to the coolant is high (shown by steep increase in temperature) at the start of the coil. But as the coolant passes along the length of coil, the temperature of the coolant goes on increasing. As the temperature of the coolant approaches the bath temperature, it reduces the driving force for the heat transfer between the hot fluid bath and the coolant in the coil. Because of this reduction in the rate of heat transfer, the temperature of the coolant tends to cease at the higher end of the coil.

OVERALL HEAT TRANSFER COEFFICIENT

The graph below explains the overall heat transfer coefficient (OHTC) for various flow rates and different bath liquids.

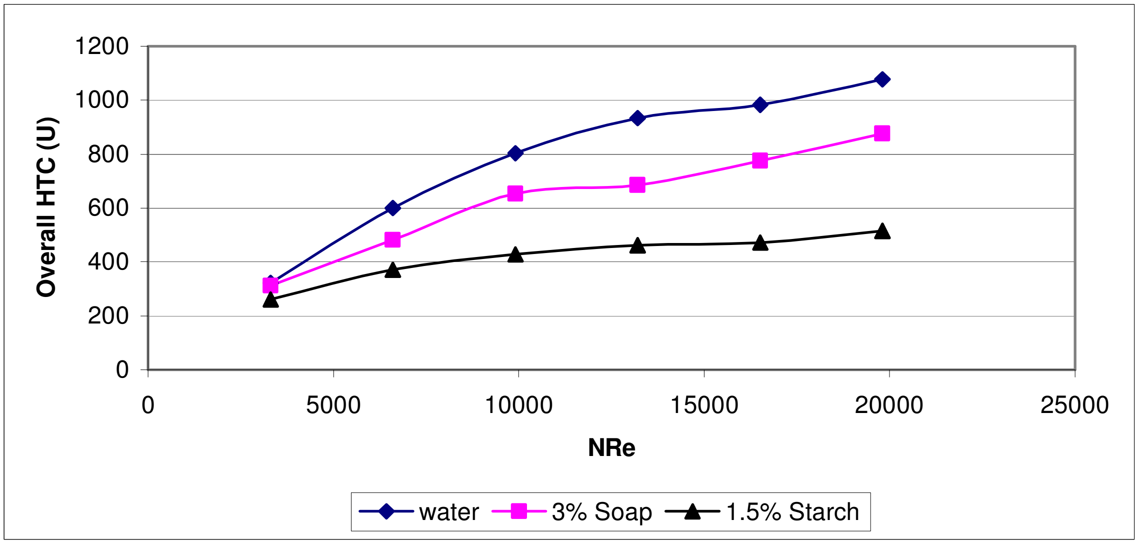


Fig. 12 Graph of OHTC (U) v/s NRe

From the graph it can be clearly seen that OHTC is maximum for water as bath liquid and lowest for 1.5% starch solution. This happens due to the fact that water provides less resistance to heat transfer than soap and starch solution.

OHTC depends on both, outside and inside heat transfer coefficient (refer pg. 2). As the resistance provided by the outside liquid bath is more, due to presence of natural convection, and less in coil due to presence of forced convection, OHTC shifts more towards the lower value of HTC. Even if the value of the inside HTC increases by 1000, there is not much change in overall value of OHTC. For example, as

$$\frac{1}{U} = \frac{1}{h_i} + \frac{1}{h_o}$$

For NRe = 9905.685, by using above eq. h_o is calculated.

Bath liquid	**U ($W/m^2\,^oK$)**	**h_i ($W/m^2\,^oK$)**	**h_o ($W/m^2\,^oK$) (Calculated)**
Water	803.019	2495.09	1184.114
Soap Sol.	653.685	3676.98	795.022
Starch Sol.	428.98	3676.98	485.63

From above table it can be seen that even after having high inside HTC, the OHTC reduces to a value which is more nearer to outside HTC.

INSIDE HEAT TRANSFER COEFFICIENT

The graph below shows the value of inside HTC at various flow rates and for different bath liquids.

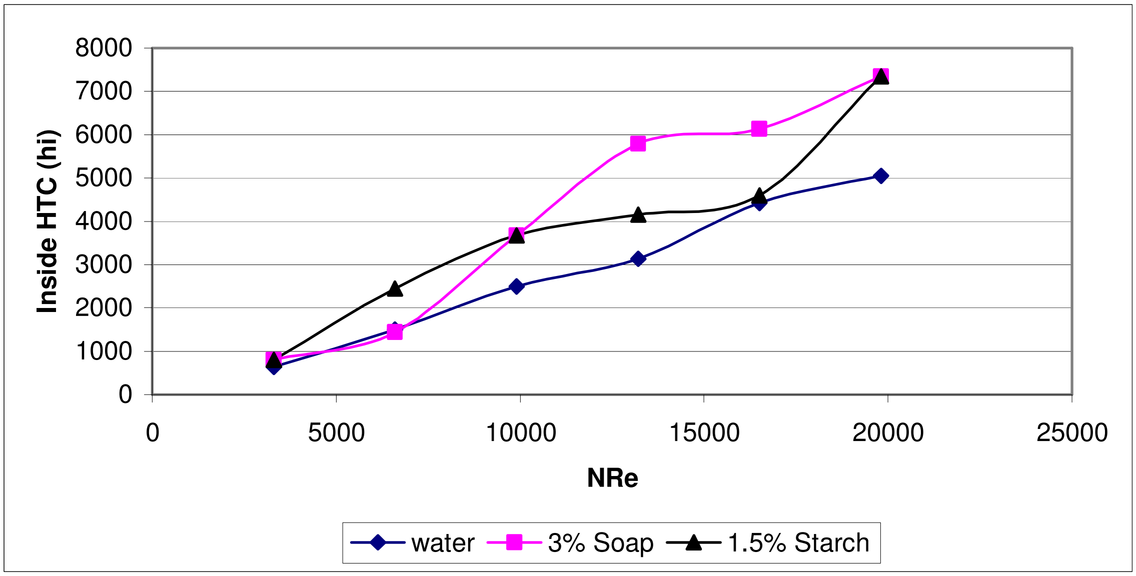


Fig. 13 Graph of Inside HTC v/s NRe

The inside HTC for water bath is low as compared to soap & starch sol. bath. But it does not make much difference, as the HTC is totally controlled by the outside HTC and also OHTC for water bath is very high, throughout, as explained earlier. OHTC is used generally for designing of heat exchanger and not the inside HTC.

Due to this sudden decrease in inside HTC, several runs were repeated for water bath, but almost same results were obtained.

6
BATCH COOLING

6.1 INTRODUCTION

Heating and cooling for batch process are some of the most common stages in chemical process plant. Inadequate understanding for these process often results in higher than average number of design and startup problems. Design & start up problems are given in literature (3)

These problems can be minimized if we have a good appreciation of how the different batch heat transfer variables relate to each other.

To obtain this, several easy to use equations have been developed for no change of phase in the medium. These functions will allow the quantities to be calculated as a function of time:

1. Batch temperature
2. Heat load or rate of heat transfer
3. Flow rate of heat transfer medium
4. Final temperature of heat transfer medium

6.2 EXPERIMENTAL PROCEDURE

The experiment is carried out in following order:

1. The tank is first filled with bath liquid up to certain height where the coils are fully immersed.
2. The heater is started to heat the bath liquid up to certain desired temperature is attained. In our case the temperature attained 80^oC. After that the heating was stoped.
3. The cooling water was started and adjusted to certain fixed flow rate (1, 3, 5 lpm).

4. Data was gathered for the specific time interval, like the bath temperature and the outlet temperature of cooling water.
5. The experiment was run, till the bath attained 35^{o}C or for 1 hr, which ever came first.

$$Q = m\ C_p\ (T_2 - T_1)$$

Where,

m = Mass Flow rate, gm/sec

C_p = Specific heat of liquid, J/gm ^{o}K

T_1 = Inlet temp of Coolant, ^{o}C

T_2 = Outlet temp of Coolant, ^{o}C

The above equation was used for determining the rate of heat transfer. From the tables ahead, it can be seen that the rate of heat transfer is high when the bath temperature is high and goes on decreasing as the bath temperature decreases. As we increased the flow rate of cooling water, the bath temperature dropped suddenly.

Further a simulation of batch cooling is done, which matches the experimental readings of the batch cooling.

The experiment was carried out to determine, how long it will take to bring the bath temperature to desired level and what will be the outlet temperature of the cooling water at different coolant flow rates.

Given ahead are experimental readings for batch cooling of water, 3% soap and 1.5% starch solution at 1, 3, 5 lpm.

Date: 01/03/05

Initial Temperature of Bath: 80°C

Initial temperature of Coolant: 32°C

Liquid in bath: Water

FLOW RATE: 1 lpm

Time (min)	Bath Temp (°C)	Outlet Temp of Coolant (°C)	Q ($W/m^2 {}^oK$)
0	80	-	-
2	78	74	2929.72
4	76	72	2790.21
6	73	70	2650.70
8	70	67	2441.43
10	67	65	2301.92
12	64	63	2162.41
14	62	60	1953.15
16	59	58	1813.64
18	57	56	1674.13
20	55	55	1604.37
22	53	53	1464.86
25	51	51	1325.35
30	48	57	1046.33
35	45	45	906.82
40	43	43	767.31
45	41	41	627.79
50	40	39	488.29
55	39	38	418.53
60	38	37	348.77

Date: 01/03/05

Initial Temperature of Bath: 80^{o}C

Initial temperature of Coolant: 32^{o}C

Liquid in bath: Water

FLOW RATE: 3 lpm

Time (min)	Bath Temp (^{o}C)	Outlet Temp of Coolant (^{o}C)	Q (W/m^{2} ^{o}K)
0	80	-	-
2	75	68	7533.58
4	70	63	6487.25
6	65	59	5650.18
8	60	54	4603.85
10	56	51	3976.05
12	53	49	3557.52
14	50	46	2929.72
16	48	44	2511.19
18	46	43	2301.92
20	44	41	1883.39
22	43	40	1674.13
25	42	39	1464.86
30	39	37	1046.33
35	38	36	837.06
40	37	35	627.8
45	36	35	627.8
50	36	35	627.8

Date: 01/03/05

Initial Temperature of Bath: 80^{o}C

Initial temperature of Coolant: 32^{o}C

Liquid in bath: Water

FLOW RATE: 5 lpm

Time (min)	**Bath Temp (^{o}C)**	**Outlet Temp of Coolant (^{o}C)**	**Q (W/m^2 ^{o}K)**
0	80	-	-
2	73	60	9765.75
4	66	55	8021.87
6	60	50	6277.98
8	55	46	4882.87
10	51	43	3836.54
12	48	41	3138.99
14	45	39	2441.43
16	43	38	2092.66
18	41	36	1395.1
20	40	36	1395.1
22	39	35	1046.33
25	37	34	697.55
30	36	33	348.77
35	35	33	348.77
40	35	33	348.77
45	34	33	348.77
50	34	33	348.77

Date: 28/02/2005

Initial Temperature of Bath: 80^{o}C

Initial temperature of Coolant: 32^{o}C

Liquid in bath: 3% soap solution

FLOW RATE: 1 lpm

Time (min)	Bath Temp (^{o}C)	Outlet Temp of Coolant (^{o}C)	Q (W/m^{2} ^{o}K)
0	80	-	-
2	78	74	2929.72
4	75	69	2580.95
6	72	67	2441.43
8	69	65	2301.92
10	67	63	2162.41
12	64	60	1953.15
14	60	57	1743.88
16	58	55	1604.37
18	56	54	1534.61
20	54	52	1395.10
22	52	50	1255.59
25	49	47	1046.33
30	46	44	837.06
35	43	41	627.79
40	40	39	488.28
45	39	38	418.53
50	38	37	348.77
55	36	35	209.27
60	36	35	209.27

Date: 28/02/2005

Initial Temperature of Bath: 80^{o}C

Initial temperature of Coolant: 32^{o}C

Liquid in bath: 3% soap solution

FLOW RATE: 3 lpm

Time (min)	Bath Temp (^{o}C)	Outlet Temp of Coolant (^{o}C)	Q (W/m^{2} ^{o}K)
0	80	-	-
2	76	66	7115.05
4	70	61	6068.72
6	66	58	5440.92
8	62	54	4603.85
10	58	51	3976.05
12	55	49	3557.52
14	52	46	2929.72
16	49	44	2511.19
18	47	42	2092.66
20	45	41	1883.39
22	44	40	1674.13
25	42	38	1255.59
30	39	36	837.06
35	37	35	627.79
40	36	34	418.53
45	35	34	418.53
50	35	34	418.53

Date: 28/02/2005

Initial Temperature of Bath: 80^{o}C

Initial temperature of Coolant: 32^{o}C

Liquid in bath: 3% soap solution

FLOW RATE: 5 lpm

Time (min)	Bath Temp (^{o}C)	Outlet Temp of Coolant (^{o}C)	Q (W/m^{2} ^{o}K)
0	80	-	-
2	74	59	9416.98
4	67	54	7673.09
6	62	50	6277.98
8	57	47	5231.65
10	54	44	4185.32
12	51	42	3487.77
14	48	40	2790.21
16	46	39	2441.43
18	43	37	1743.88
20	42	36	1395.1
22	41	36	1395.1
25	39	35	1046.33
30	37	34	697.55
35	36	33	348.77
40	35	33	348.77
45	34	33	348.77
50	34	33	348.77

Date: 4/03/2005

Initial Temperature of Bath: 80°C

Initial temperature of Coolant: 32°C

Liquid in bath: 1.5% starch solution

FLOW RATE: 1 lpm

Time (min)	Bath Temp (°C)	Outlet Temp of Coolant (°C)	Q ($W/m^2\,°K$)
0	80	-	-
2	77	68	2511.19
4	74	66	2371.68
6	72	63	2162.41
8	69	60	1953.15
10	67	57	1743.88
12	65	54	1534.61
14	64	52	1395.1
16	62	50	1255.59
18	61	48	1116.08
20	59	46	976.58
22	58	45	906.82
25	57	44	837.06
30	54	42	697.55
35	52	40	558.04
40	50	39	488.28
45	49	38	418.52
50	46	38	418.52
55	44	37	348.78
60	43	37	348.78

Date: 04/03/2005

Initial Temperature of Bath: 80°C

Initial temperature of Coolant: 32°C

Liquid in bath: 1.5% starch solution

FLOW RATE: 3 lpm

Time (min)	Bath Temp (°C)	Outlet Temp of Coolant (°C)	Q ($W/m^2\,^oK$)
0	80	-	-
2	78	61	6068.72
4	73	57	5321.65
6	69	54	4603.85
8	67	52	4185.32
10	63	49	3557.52
12	60	46	2929.72
14	58	44	2511.19
16	56	42	2092.66
18	54	41	1883.39
20	52	39	1464.86
22	50	38	1255.59
25	48	37	1046.33
30	46	35	627.79
35	44	35	627.79
40	43	34	418.53
45	41	34	418.53
50	40	33	209.26
55	39	33	209.26
60	38	33	209.26

Date: 04/03/2005

Initial Temperature of Bath: 80°C

Initial temperature of Coolant: 32°C

Liquid in bath: 1.5% starch solution

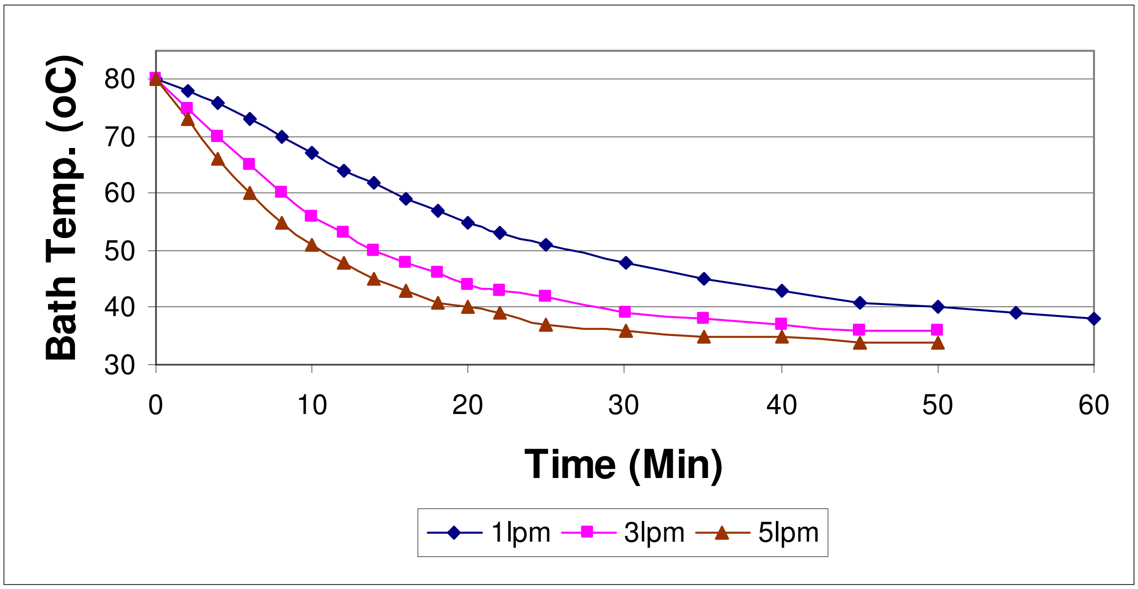
FLOW RATE: 5 lpm

Time (min)	**Bath Temp (°C)**	**Outlet Temp of Coolant (°C)**	**Q (W/m^2 °K)**
0	80	-	-
2	77	52	6975.54
4	72	50	6277.98
6	67	47	5231.65
8	63	45	4534.10
10	60	43	3836.54
12	57	41	3138.99
14	55	40	2790.41
16	53	39	2441.43
18	51	38	2092.66
20	49	37	1743.88
22	48	37	1743.88
25	46	36	1395.10
30	43	35	1046.33
35	41	34	697.55
40	40	34	697.55
45	39	34	697.55
50	38	33	348.77
55	37	33	348.77
60	36	33	348.77

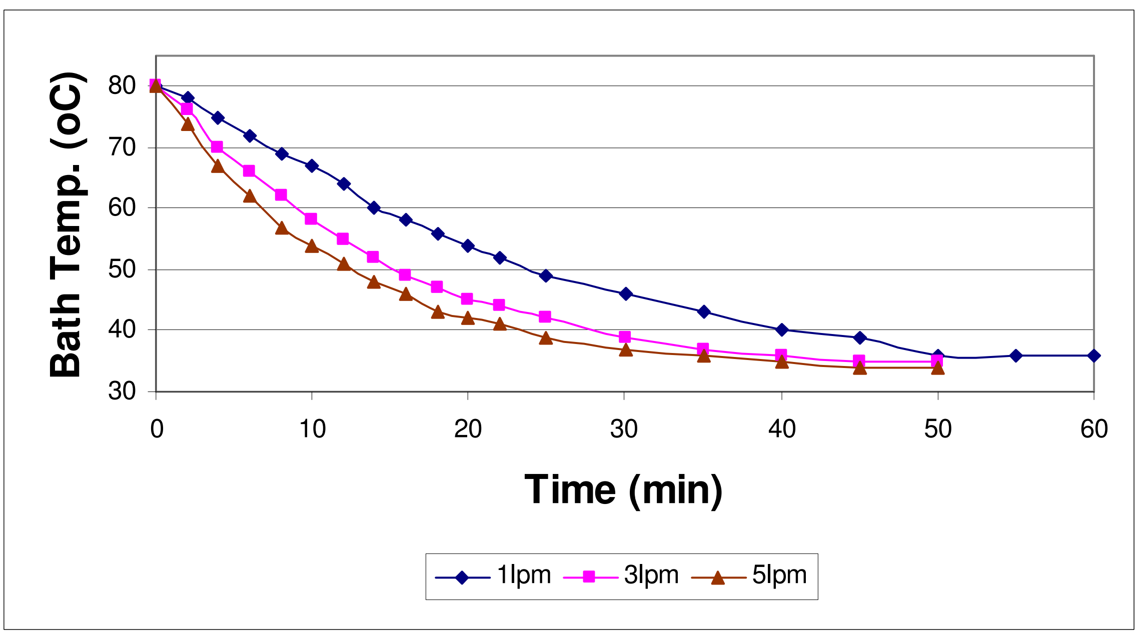
The graph below describes cooling at different flow rates for, water, soap, & starch solution.

Fig. 14 (a) (b) (c) Graph of Bath temperature v/s Time (For same bath liquid)

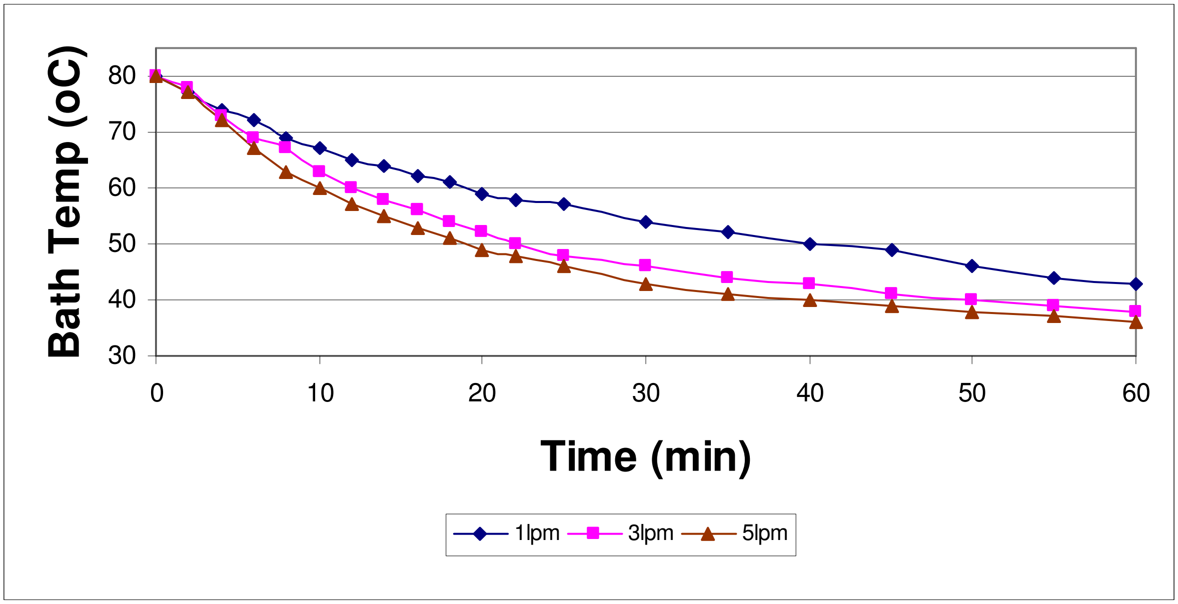
(a) <u>For Water</u>



(b) <u>For Soap Solution</u>



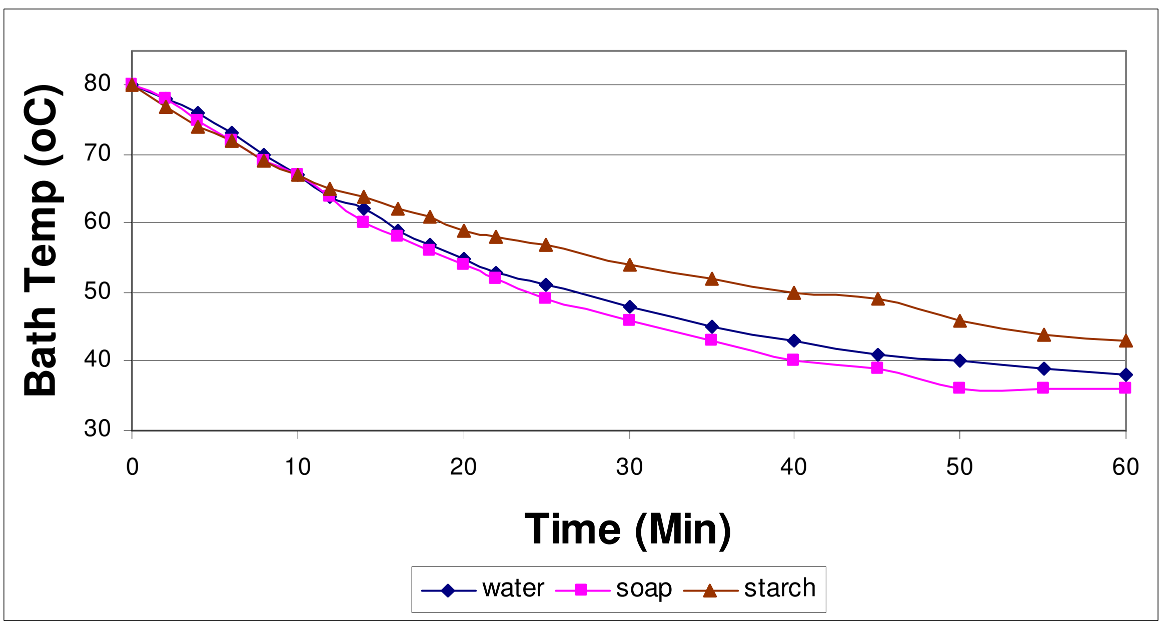
(c) For Starch Solution



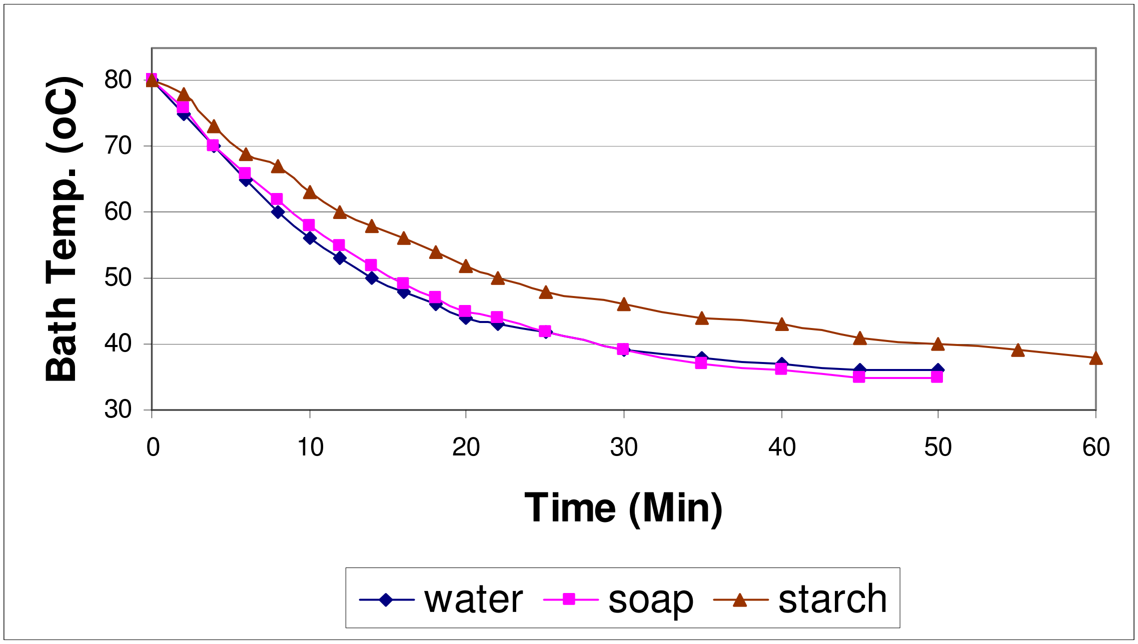
The graph below describes cooling at same flow rate for, water, soap, & starch solution.

Fig. 15 (a) (b) (c) Graph of Bath Temp v/s Time

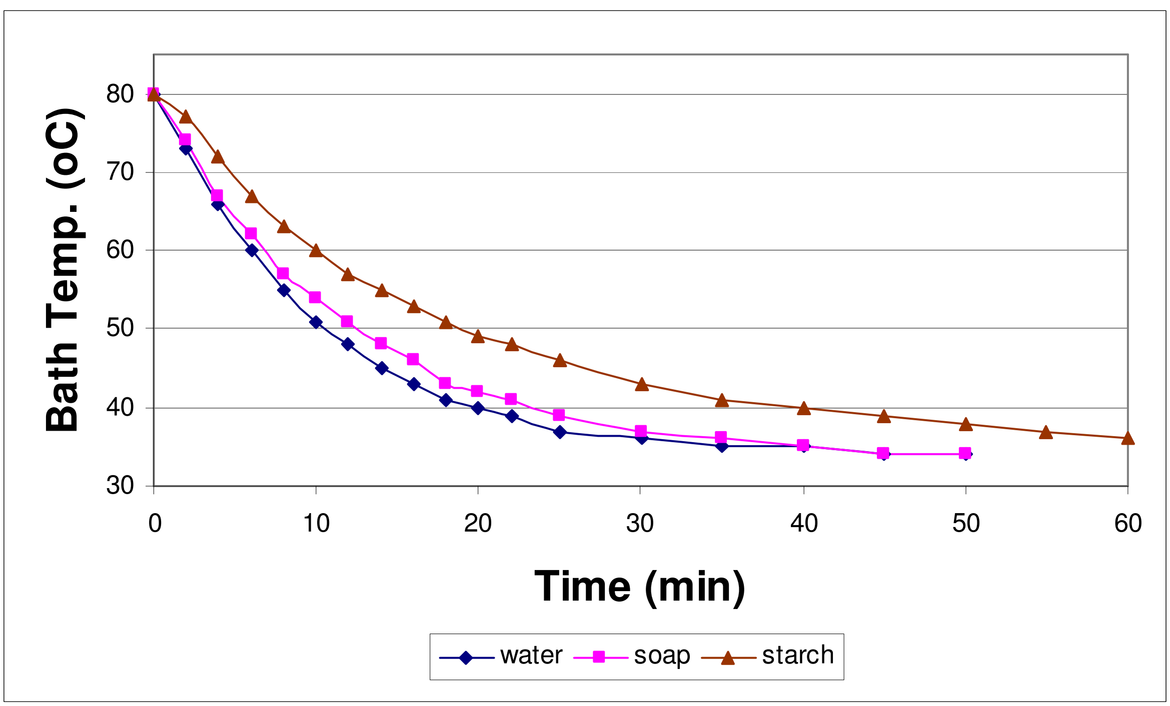
(a) For 1 LPM



(b) **For 3 LPM**



(c) **For 5 LPM**



6.3 RESULTS & DISCUSSION

Experimentation for batch cooling was carried out to determine the time taken for a particular bath to cool down to required temperature, the outlet temperature of the coolant & the rate of heat transfer, with respect to time.

From the experiment it was determined that the rate of heat transfer reduces drastically, once the temperature of the bath liquid goes on decreasing, because of reduction in driving force (temperature difference). As the bath temperature decreases, the outlet temperature of the coolant also approaches the bath temperature.

Graphs plotted above for batch cooling are divided in 2 sections:

1. For a particular bath liquid comparison for different flow rates &
2. At particular flow rate, comparison for different bath liquids.

For a particular bath, as we increase the flow rate of the coolant, the rate of heat transfer also increases and the bath cools much faster as seen from the graphs above.

From the second type of graph, comparison is done for different fluid baths at same flow rate of coolant. From this, it is clear that, water bath cools much faster & the starch solution bath cools much slower. This happens due to the fact that, the resistance to heat transfer is much higher in starch solution than in water & soap solution. This resistance is provided by the colloidal particles present in suspended form in the solution & also plays a major role in reducing the natural convection taking place in the liquid bath.

Ahead simulation is done for batch cooling process. The simulation results are then matched with experimental results.

7
MODELING & SIMULATION

7.1 INTRODUCTION

Mathematical Model for a process is defined as a system of equations whose solutions, given specified input data, is representative of the reference of the process to a corresponding set of inputs.

Process simulation represents some aspects of the real world by numbers or symbols. These are easily manipulated to facilitate their study. Each simulation problem is associated to a corresponding mathematical model. Since their can be many ways to solve a set of equations representing a mathematical model, it is necessary have a simulation strategy which ensures that the simulation problem is solved efficiently and that the simulation results are reliable (reliability depends on the model accuracy which may otherwise end up with incorrect simulation results). Each step process simulation is linked to each other, which can be large enough to justify the use of the computer to solve the problem.

Dependent variables = f (Independent variables, Parameters, Forcing functions)

Thus the uses of model can be summarized as follows:

1. In design / sizing the process equipment for dynamic performance.
2. Studying the interaction of different parts of the process particularly during material recycling or heat interaction.
3. For determining chemical kinetic mechanism and parameters from pilot plant studies (R & D)

In this chapter we have tried to simulate the differential equations to obtain temperature change with respect to time and its corresponding Heat Transfer Rate as a comparative study and also as a test of accuracy against the value of the experimentation that has been carried out (i.e. batch cooling) whose values has been displayed in previous chapter.

7.2 EQUATIONS USED

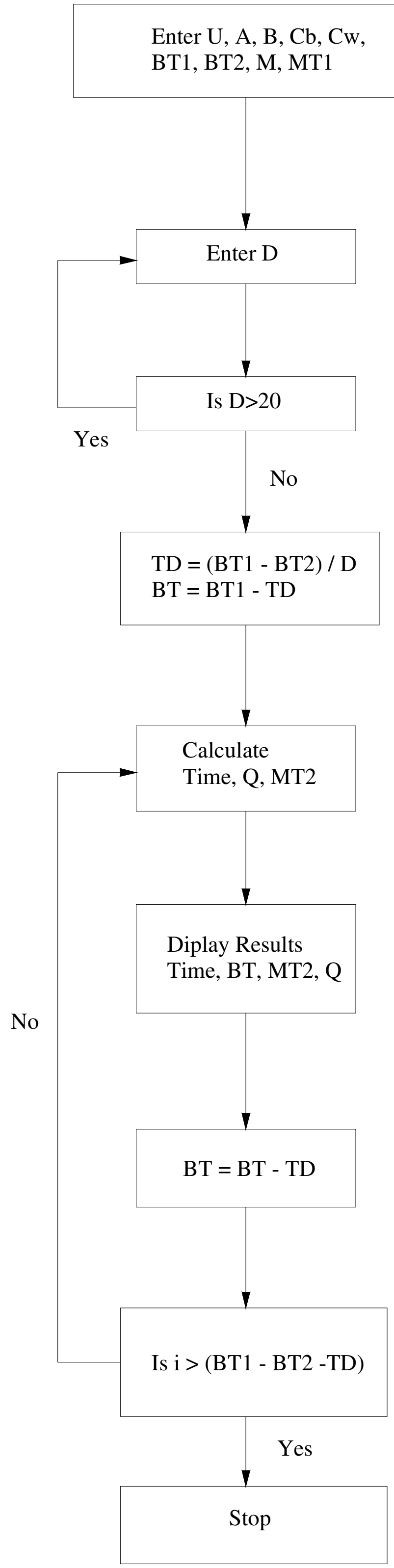
$$\theta = \frac{B\,C_b}{W\,C_w} \left(\frac{1}{1 - e^{-UA/WCw}} \right) \ln \left(\frac{T_{b1} - T_{w1}}{T_b - T_{w1}} \right)$$

$$q = B\,C_b\,K\,(T_{b1} - T_{w1})\,e^{-K\theta}$$

$$K = \frac{W\,C_w}{B\,C_b} \left(1 - e^{-UA/WCw} \right)$$

$$Tw = \frac{Q}{W\,C_w} + T_{w1}$$

7.3 ALGORITHM



7.4 VISUAL BASIC CODING

VB CODING (FORM: HEAT TRANSFER CALCULATIONS)

```
Private Sub butCalc_Click()

'check
If tbTB.Text = "" Or tbIn.Text = "" Or tbOut.Text = "" _
    Or tbT1.Text = "" Or tbT2.Text = "" Or tbT3.Text = "" _
    Or tbT4.Text = "" Or tbT5.Text = "" Or tbT6.Text = "" _
    Or tbLPM.Text = "" Then
    MsgBox "Please check again. Some data is missing.", vbInformation,
"Data Missing"

Else

'Initialization
A = (3.14 * 0.0075 * 14.5)
Cp = 4.18
K = 0.614
meu = 0.857

'Data gathering
Tb = Val(tbTB.Text)
Tin = Val(tbIn.Text)
Tout = Val(tbOut.Text)
T1 = Val(tbT1.Text)
T2 = Val(tbT2.Text)
T3 = Val(tbT3.Text)
T4 = Val(tbT4.Text)
T5 = Val(tbT5.Text)
T6 = Val(tbT6.Text)
LPM = Val(tbLPM.Text)
Qin = Val(tbQin.Text)

'Flow rate
M = 16.66 * LPM
g = M / (3.14 / 4 * 0.0075 ^ 2)
```

```
'Temp calculation
dT = Tout - Tin
Tav = (T1 + T2 + T3 + T4 + T5 + T6) / 6
Tm = (Tout + Tin) / 2

'Data reduction
Qout = M * 4.187 * dT
Qerr = (Qin - Qout) / Qin * 100
U = Qout / (A * (Tb - Tm))
Hi = Qout / (A * (Tav - Tm))

'Dimensionless no.
Nre = (0.0075 * g) / meu
Pr = Cp * meu / K
Nu = Hi * 0.0075 / K

'Display Results
tbU.Text = U
tbHi.Text = Hi
tbQout.Text = Qout
tbQerr.Text = Qerr
tbRe.Text = Nre
tbPr.Text = Pr
tbNu.Text = Nu
tbM.Text = M
tbTav.Text = Tav
tbTm.Text = Tm

End If
End Sub

Private Sub cmdClear_Click()
tbTB.Text = ""
tbIn.Text = ""
tbOut.Text = ""
tbT1.Text = ""
tbT2.Text = ""
tbT3.Text = ""
```

```
tbT4.Text = ""
tbT5.Text = ""
tbT6.Text = ""
tbLPM.Text = ""
tbTB.SetFocus

End Sub

Private Sub Form_Load()
Dim Tb, Tin, Tout, dT, T1, T2, T3, T4, T5, T6, Tm, Tav, _
    Nre, Nrec, Pr, De, Gr, Gz, Nu, Ry, H1, H2, _
    LPM, g, Den, Qin, Qout, Qerr, Hi, U, f, _
    L1, L2, L3, L4, L5, L6, meu, Cp, K, _
    Hi1, Hi2, Hi3, Hi4, Hi5, Hi6, A As Single
End Sub
```

VB CODING (FORM: BATCH COOLING SIMULATION)

```
Private Sub cmdRun_Click()

'Check
If tbU.Text = "" Or tbA.Text = "" Or tbB.Text = "" Or tbCb.Text = "" _
    Or tbCw.Text = "" Or tbBT1.Text = "" Or tbBT2.Text = "" _
    Or tbD.Text = "" Or tbMT1.Text = "" Or tbM.Text = "" _
    Or Val(tbD.Text) > 20 Or Val(tbD.Text) <= 1 Then

MsgBox "Please Check again. Some Data is ' MISSING '." + Chr(13) &
Chr(10) + _
        "OR" + Chr(13) & Chr(10) + _
        "Wrong value of D is given" + Chr(13) & Chr(10) + _
        "It should be between 2 & less than or equal to 20",
vbInformation, "Data Missing"

Else

'Data Gathering
U = Val(tbU.Text)
A = Val(tbA.Text)
```

```
B = Val(tbB.Text)
Cb = Val(tbCb.Text)
Cw = Val(tbCw.Text)
BT1 = Val(tbBT1.Text)
BT2 = Val(tbBT2.Text)
D = Val(tbD.Text)
MT1 = Val(tbMT1.Text)
M = Val(tbM.Text)

'convert
BT1 = BT1 + 273         ‘temp in kelvin
BT2 = BT2 + 273
M = M / 60              ‘Kg / sec
MT1 = MT1 + 273

TD = (BT1 - BT2) / D
BT = BT1 - TD

Dim i As Single
i = 0

BT1 = BT1 - 273
rtbReT.Text = "0" & Chr(13) & Chr(10)
rtbReBT.Text = BT1 & Chr(13) & Chr(10)
rtbReQ.Text = Q & Chr(13) & Chr(10)
rtbReMT2.Text = MT2 & Chr(13) & Chr(10)
BT1 = BT1 + 273

‘Loop for reducing bath temp with time
For i = 0 To (BT1 - BT2 - TD) Step TD

    X = Log((BT1 - MT1) / (BT - MT1))
    Y = 1 - (1 / Exp((U * A) / (M * Cw)))
    t = (((B * Cb) / (M * Cw)) * X) / Y
    Q = (((M * Cw) * Y * (BT1 - MT1)) / (Exp(((M * Cw) / (B * Cb)) * Y
* t))) * 0.95
    MT2 = (Q / (M * Cw)) + MT1
```

```
    t = t / 60  'convert sec into min
    BT = BT - 273   'convert K to oC
    MT2 = MT2 - 273 'convert K to oC

'Display result
    rtbReT.Text = rtbReT.Text & t & Chr(13) & Chr(10)
    rtbReBT.Text = rtbReBT.Text & BT & Chr(13) & Chr(10)
    rtbReQ.Text = rtbReQ.Text & Q & Chr(13) & Chr(10)
    rtbReMT2.Text = rtbReMT2.Text & MT2 & Chr(13) & Chr(10)

    t = t * 60      'convert min to sec
    BT = BT + 273   'convert oC to oK
    MT2 = MT2 + 273 'convert ok to oC

    BT = BT - TD
Next i

ssTab.Tab = 2
End If
End Sub

Private Sub Form_Load()
ssTab.Tab = 1

Dim nl As String
nl = Chr(13) & Chr(10)

'Display Nomenclature in Text Box
rtbNom.Text = " U = Overall Heat Transfer Coefficient, Watt/(m2 K)" +
nl _
    & " A = Area of heat transfer, m2" + nl _
    + " B = Mass of Batch Liquid, kg" + nl _
    & " Cb = Specific heat of batch liquid, J/(Kg K)" + nl _
    & " Cw = Specific heat of heat transfer liquid, J/(Kg K)" + nl _
    & " BT1 & BT2 = Initial and final bath temperature, C" + nl _
    & " D = No. of iterations" + Chr(13) & Chr(10) _
    & " Q = Rate of heat transfer, watt" + nl _
    & " t = The time to cool, min" + nl _
```

```
    & " MT1 & MT2 = Inlet & Outlet temperature of heat transfer liquid,
C" + nl _
    & " M = Mass flow rate, kg/min"

Dim U, A, B, Cb, Cw, BT1, BT2, BT, D, Q, t, M, MT1, MT2, X, Y, TD, K As
Double
End Sub
```

VB CODING (FORM: BATCH COOLING)

```
Private Sub cmdCalc2_Click()

'Data Gathering
M = Val(tbM.Text)
Cp = Val(tbCp.Text)
T1 = Val(tbT1.Text)
T2 = Val(tbT2.Text)

M = M * 16.66                  'LPM to gm/sec
Q = M * Cp * (T2 - T1)         'Calc Q
tbQ.Text = Q                   'Display result
End Sub

Private Sub cmdClear2_Click()
tbT2.Text = ""
tbT2.SetFocus
End Sub

Private Sub Form_Load()
Dim M, Cp, T1, T2, Q As Single
End Sub
```

VB CODING (FORM: MDI FORM)

```
Private Sub frmHTC_Click()
Load frmHT       ‘Load Heat Transfer Calc form
End Sub

Private Sub mnuBC_Click()
Load frmBCool    ‘Load Batch Cooling Calc form
End Sub

Private Sub mnuBCS_Click()
Load frmSimu     ‘Load Batch Cooling Simulation form
End Sub

Private Sub mnuClose_Click()
Unload Me        ‘Close Application
End Sub
```

VB CODING (FORM: SPLASH SCREEN)

```
Private Sub Form_KeyPress(KeyAscii As Integer)
    Unload frmSplash
    'Load MDIForm1
    MDIForm1.Show
  End Sub

Private Sub Form_Load()
    lblVersion.Caption = "Version " & App.Major & "." & App.Minor
& "." & App.Revision
    lblProductName.Caption = "Simulator"
End Sub

Private Sub Frame1_Click()
    Unload frmSplash
    MDIForm1.Show
End Sub
```

7.5 RESULTS OF SIMULATION

Nomenclature used in Simulation

U = Overall Heat Transfer Coefficient, Watt/(m^2 K)

A = Area of heat transfer, m^2

B = Mass of Batch Liquid, kg

Cb = Specific heat of batch liquid, J/(Kg K)

Cw = Specific heat of heat transfer liquid, J/(Kg K)

BT1 & BT2 = Initial and final bath temperature, ^oC

D = No. of iterations

Q = Rate of heat transfer, watt

t = The time to cool, min

MT1 & MT2 = Inlet & Outlet temperature of heat transfer liquid, ^oC

M = Mass flow rate, lpm

Important Note

This simulation has been done for batch cooling process, considering an ideal system. Hence the results of the simulation may also vary accordingly when compared to original results obtained by performing the experiments. This may happen due to heat losses occurring in the real system. This heat loss also varies with respect to temperature i.e. heat loss is high when the bath temperature is high & the losses goes on reducing when the bath temperature decreases.

From the results it can be seen that the outlet temperature of cooling water & the rate of heat transfer almost matches with experimental results.

Result given below is for water as bath liquid for 3 lpm.

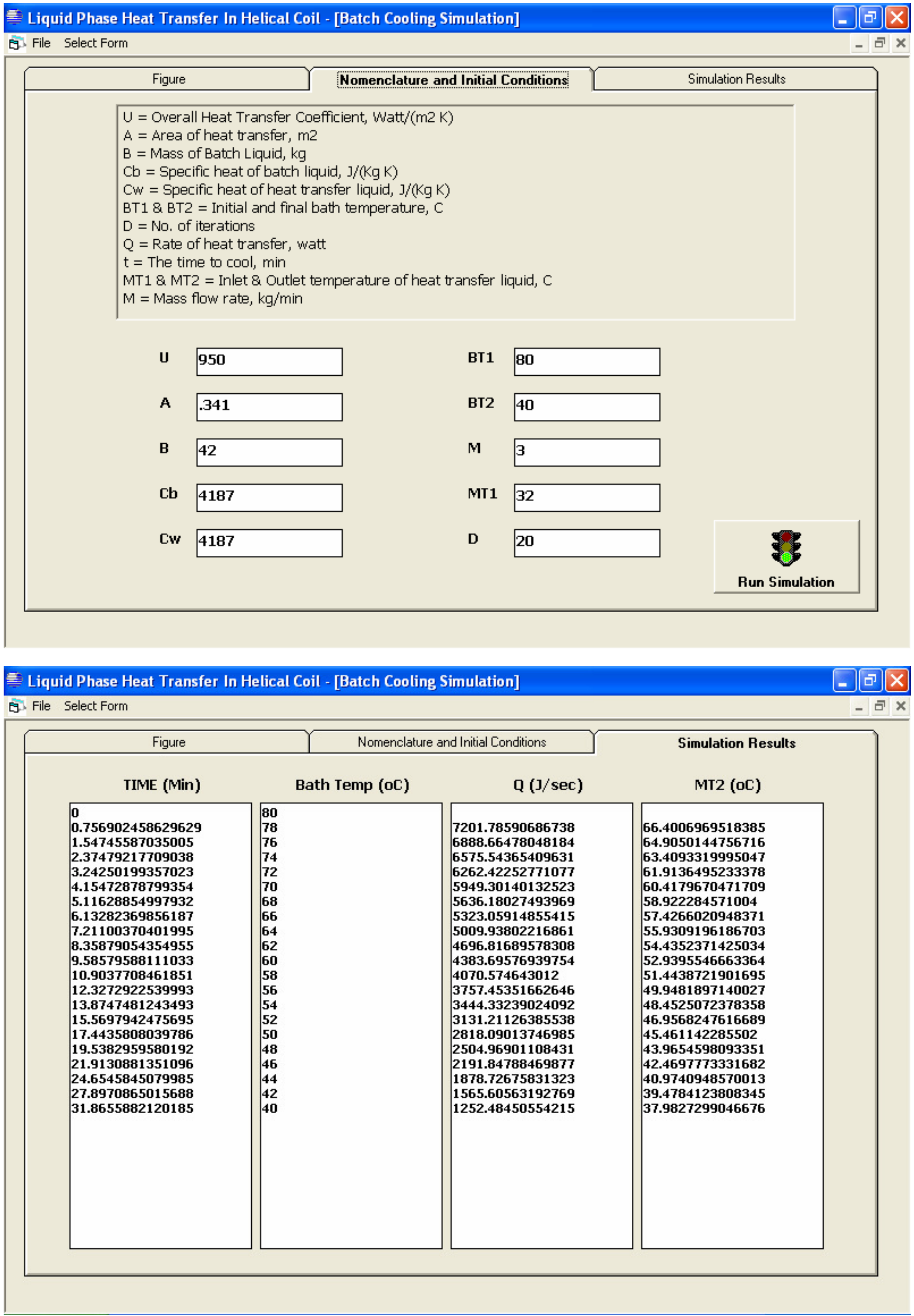


Fig. 16 GUI for simulation program (i/p and o/p)

Simulation for 3 LPM : Water Bath

U	= 950		BT1	=	80
A	= 0.341		BT2	=	40
B	= 42		M	=	3
Cb	= 4187		MT1	=	32
Cw	= 4187		D	=	20

Time	Bath Temp	Q	MT2
0	80		
0.756902458629629	78	7201.78590686738	66.4006969518385
1.54745587035005	76	6888.66478048184	64.9050144756716
2.37479217709038	74	6575.54365409631	63.4093319995047
3.24250199357023	72	6262.42252771077	61.9136495233378
4.15472878799354	70	5949.30140132523	60.4179670471709
5.11628854997932	68	5636.18027493969	58.922284571004
6.13282369856187	66	5323.05914855415	57.4266020948371
7.21100370401995	64	5009.93802216861	55.9309196186703
8.35879054354955	62	4696.81689578308	54.4352371425034
9.58579588111033	60	4383.69576939754	52.9395546663364
10.9037708461851	58	4070.574643012	51.4438721901695
12.3272922539993	56	3757.45351662646	49.9481897140027
13.8747481243493	54	3444.33239024092	48.4525072378358
15.5697942475695	52	3131.21126385538	46.9568247616689
17.4435808039786	50	2818.09013746985	45.461142285502
19.5382959580192	48	2504.96901108431	43.9654598093351
21.9130881351096	46	2191.84788469877	42.4697773331682
24.6545845079985	44	1878.72675831323	40.9740948570013
27.8970865015688	42	1565.60563192769	39.4784123808345
31.8655882120185	40	1252.48450554215	37.9827299046676

The 2 graphs given below give the comparison between the actual experimental readings and simulated readings for bath temperature and coolant outlet temperature. It is clear from the graph that the simulated results almost match the experimentally obtained results and the mathematical model matches the real system to great extent.

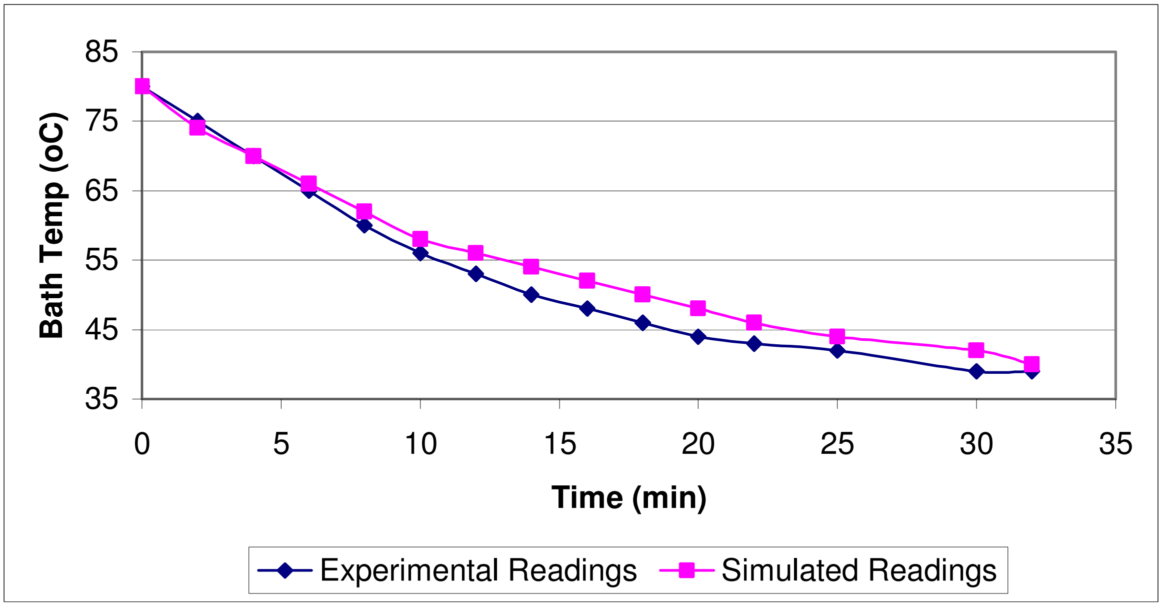


Fig. 17. Graph of Bath temp v/s Time

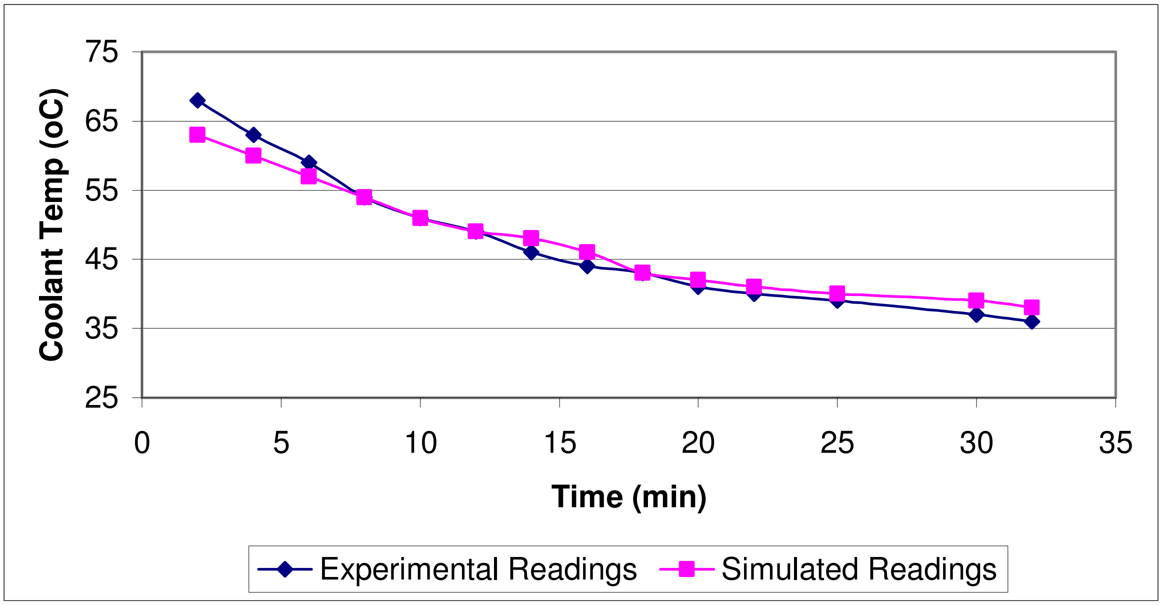


Fig. 18 Graph of Coolant outlet temp v/s Time

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CONCLUSION

This experimental project was carried out with satisfactory resul7ts. The results and discussion is made at the end of each topic, where ever necessary. The following points are discussed for concluding this project:

- Higher heat transfer coefficient was obtained as N_{Re} goes on increasing in side the helical coil. This happens due to the turbulence taking place in the coil, even at low fluid flow rates.

  Due to the presence of secondary fluid flow, the HTC is also very high in coiled tube. The secondary flow results due to centrifugal action that a fluid is subjected to, when flowing in coil.
- Higher values of U (OHTC) were obtained for water as bath liquid and least for starch solution as bath liquid. This happens due to the fact that, starch offers more resistance to heat transfer than soap solution and water because of the suspended particles present in both, the soap & starch solution.
- Experiment for batch cooling was also done. Following points were determined :
  a. For a particular bath liquid, as we go on increasing the flow rate, the batch cools much faster because of increase in rate of heat transfer.
  b. For a particular flow rate, comparison was done for all the three bath liquids. Water cooled much faster than soap & starch solution batch, because starch solution offered more resistance to heat transfer than soap solution & water.

FURTHER STUDIES IN THIS FIELD

For further development in the field of heat transfer in helical coil, some important points are discussed below:

1. **Study of two different coils**

   A comparative study between 2 coils of same inside tube diameter but different coil diameters can be done and study the effect of coil diameter on HTC.

2. **Heat transfer with agitation**

   Study of heat transfer with use of suitable agitator can be done, as agitator increases the heat transfer in the liquid bath, which otherwise is due to natural convection. Its effect on HTC can be studied.

3. **Use of different coolants**

   In this experiment on water was used as coolant. But other coolants like brine solution & Dowtherm G can be used in closed loop and its effect on HTC can be studied.

4. **Study of friction factor**

   In helical coils, as there is large pressure drop, study of friction factor at various values of Reynolds number can be also done. As the pressure drop is quite high in coils, it is recommended to use shorter lengths of coil (say up to 4 to 5 meter).

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