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DETERMINATION OF HEAT TRANSFER COEFFICIENTS IN STIRRED TANK SYSTEMS

by

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DETERMINATION OF HEAT TRANSFER COEFFICIENTS

IN STIRRED TANK SYSTEMS

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HEAT TRANSFER COEFFICIENT

(- In agitated vessels - In coiled vessels)

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ABSTRACT

Heat transfer coefficients for helically coiled and continuously stirred tanks were determined using flat paddle turbine impellers. Heat transfer experiments have been carried out by varying the inlet temperature, flowrate of hot stream and agitator speed in the two flat bottom cylindrical stirred tanks in series. Experiments were also repeated for a single tank.

The investigation was conducted under both steady-state and unsteady-state conditions with water being used, as the liquid to be mixed. The individual film heat transfer coefficients were calculated from the experimental overall heat transfer coefficients by using the Modified-Wilson Graphical Method. Two computer programs were also developed to check the validity of the analytical model used, and to compute film heat transfer coefficients and temperatures.

A Reynolds number range of 19439 to 76727 was used for the agitated side, that there has been very little investigation in this region. In the coil side, the Reynolds number range was varied from 1100 to 14000. The convective heat transfer coefficients for unsteady-state conditions were found to have the same value as for steady-state conditions. The values of the individual film heat transfer coefficients found were in agreement with the previously published values

for similar cases and the analytical model for heat transfer in two consecutive stirred tanks gave same results in agreement with the experimental results.

Agitator speed was changed between 200 and 500 rpm. Higher values of heat transfer coefficients were observed with increasing agitator speeds.

ÖZET

Serpantinli ve sürekli karıştırıcılı sistemlerde açık düz bıçaklı turbin karıştırıcılar kullanılarak ısı transfer katsayıları hesaplanmıştır. İkili tank sisteminde yapılan deneylerde karıştırıcı hızı, sıcak su giriş sıcaklığı ve akış hızı değiştirilmiş ve bu deneyler tek tank için tekrar edilmiştir.

Deneyler sırasında gerek tank içinde gerekse serpantin içinde su kullanılmış, kararlı ve kararsız durumlar incelenmiştir. Doğrudan deneysel değerler kullanılarak hesaplanan bileşik ısı transfer katsayısından, Wilson'un Grafik Yöntemi kullanılarak iç ve dış ısı transfer katsayıları hesaplanmıştır. Biri tek tank, diğeri iki tanklı sistem için olmak üzere iki bilgisayar programı hazırlanmış, ampirik denklemler ve geliştirilen analitik modeller kullanılarak ısı transfer katsayıları ve sıcaklıklar hesaplanmıştır. Bu çalışmada karıştırıcılı taraf için Reynolds sayısı aralığı 19439-76727 olup, şimdiye kadar az denenmiş bir aralıktır. Serpantin içinde ise Reynolds sayısı aralığı 1100-14000'dir. Kararsız durum için hesaplanan konvektif ısı transfer katsayılarının kararlı durum için hesaplananlarla aynı değerde olduğu bulunmuştur. Bu çalışmada bulunan film ısı transfer katsayısı değerleri daha önce aynı durum için yayınlanan değerlere uymaktadır. Ayrıca, deneysel sonuçlar ile modelden hesaplanan sonuçların da uyumlu olduğu görülmüştür.

Karıştırıcı hızı 200'den 500 rpm'e kadar değiştirilmiştir. Artan karıştırıcı hızı ile yükselen ısı transfer katsayıları gözlemlenmiştir.

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LIST OF SYMBOLS USED

A_o, A_i, A_m	:	Outside, inside and average heat transfer areas respectively (m^2)
C_h	:	Specific heat of hot water (J/kg^oC)
C_w	:	Specific heat of cold water (J/kg^oC)
D_T	:	Tank diameter (m)
D_A	:	Agitator diameter (m)
D_H	:	Diameter of coil tubing (m)
D_c	:	Diameter of coil
ff_i, ff_{ci}	:	Fouling factor inside vessel and on coil side respectively ($m^2.^oC/W$)
HI	:	Film heat transfer coefficient inside the coil ($W/m^2.^oC$)
HO	:	Film heat transfer coefficient in agitated side ($W/m^2.^oC$)
H_ℓ	:	Liquid height in the vessel (m)
H_c	:	Coil height from the vessel bottom (m)
k	:	Thermal conductivity of water ($W/m\ ^oC$)
k_w	:	Thermal conductivity of copper coil wall ($W/m\ ^oC$)
L_c	:	Length of coil (m)
M	:	Cold water flowrate (m^3/sec)
N	:	Agitator speed (rpm)
N_{Nu}	:	Nusselt number, hD/k
N_{Re}	:	$D_A^2 N\rho/\mu$

N_{pr}	:	Prandtl number , $C_p\mu/k$
N_{Gz}	:	Greatz number, $N_{Re}\ N_{pr}\ D_H/L$
N_{Gr}	:	Grashoff number, $(L^3 g^2 \rho\beta\Delta T)/\mu^2$
N_{st}	:	Stanton number, $N_{Nu}/N_{Re}\ N_{pr}$
Q	:	Heat transfer rate, Cal/hr
T_1, TH1	:	Inlet temperature of hot stream to tank II (^oC)
T_2, TH2	:	Inlet temperature of hot stream to tank I (^oC)
T_3, TH3	:	Exit temperature of hot stream from tank I (^oC)
t_o, TCO	:	Inlet temperature of cold stream to tank I (^oC)
t_1, TC1	:	Cold water temperature in tank I (^oC)
t_2, TC2	:	Cold water temperature in tank II (^oC)

SINGLE TANK

T_1, TH1	:	Inlet temperature of hot stream (^oC)
T_2, TH2	:	Exit temperature of hot stream (^oC)
t_o, TCO	:	Inlet temperature of cold stream (^oC)
t_2, TC1	:	Cold water temperature in the tank (^oC)
U	:	Overall heat transfer coefficient ($W/m^2\ ^oC$)
V_H	:	Velocity of hot stream (m/sec)
W	:	Hot stream flowrate (m^3/sec)
W_{ib}	:	Impeller blade width (m)
ρ_w	:	Density of cold water (kg/m^3)
ρ_h	:	Density of hot stream (kg/m^3)
μ	:	Viscosity at bulk temperature (kg/m sec)
μ_w	:	Viscosity at wall temperature (kg/m sec)

I. INTRODUCTION

One of the fundamental steps in numerious chemical processes is mixing by agitation. In mixing applications, the transfer of heat to or from a fluid in agitated vessels is a common operation. The rate of heat transfer is a function of the physical properties of the agitated liquid and of the heating or cooling medium, the vessel geometry, the material and the thickness of the wall and the degree of agitation. When processing is controlled by heat transfer, such variables as log-mean temperature difference and heat transfer surface area will usually predominate over the agitator variables. Mixing can only affect the outside film resistance.

In engineering work it is often necessary to estimate the overall heat transfer coefficient for a particular operation. While it is possible to calculate individual film coefficients for condensing films and for heating and cooling fluids in the jacket or coil as well as to calculate the resistance of heat transfer wall, limited data are available for the kettle side of the heat transfer surface for the agitated side of the vessel.

Common heat transfer surfaces are jackets and coils of pipe.

The common jacketed vessel provides heat surface around the periphery of the vessel, but offers the minimum area for a given volume of liquid. Immersed coils are used to provide heat transfer surface in process vessels and augment available jacketed surface. An immersed coil in an agitated vessel with or without baffle, takes one of two forms (a) helical coil type or (b) the vertical baffle type. Coils are preferred to jacketed surfaces becouse of lower cost and accomodate higher pressures in a coil or circulate fluids at higher velocities and thus attain higher heat transfer coefficients.

Numerous types of liquid mixing equipment are available for use in chemical processing. The theoretical development of liquid mixing has been slow, and in the absence of the specific design information, equipment type has quite needlessly multiplied during the years. All liquid mixing systems, however, have three factors in common: liquid being mixed, a vessel to confine the liquid and a mechanical device to generate turbulence within the system.

The aim of the present work is to determine both the internal and external film coefficients of heat transfer for a coil immersed in a stirred liquid flowing through two tanks in series, or through a single tank.

This chapter contains a brief review of heating systems for stirred tanks followed by equipment and operation in liquid mixing. In Chapter 2 the theory for heat transfer in stirred tank vessels and a literature survey are given. Method of data analysis is also discussed in the same Chapter. Mathematical modelling for a single tank and two tanks in series are presented and the computer programs are described in Chapter 3. The equipment used, and the details on the experimental study are reported in Chapter 4. Chapter 5 contains the results of the experiments and the computer analysis of data. Chapter 6 is a discussion of the results and the possible errors.

1.A HEATING SYSTEMS FOR STIRRED TANKS

Heating systems for stirred tanks can be classified as either direct or indirect. The former include direct firing and electrical heating. In indirect systems, carrier fluids are used to transport heat to the process. Carrier fluids are also used to extract heat from a process. Also indirect systems can be divided into two categories, as liquid systems and vapor systems.

In the following sections of this part, direct and indirect systems and the advantages and disadvantages of these will be discussed [1].

1.A.1 Direct Systems

Open flame direct firing is nowadays seldom used for the heating of stirred tanks. The heating tends to be uneven and the temperature is difficult to control. In addition, the processing of combustible material is hazardous. The units, although relatively inexpensive, are unwieldy since the burners, fuel supply and controls must be at the process location.

There are various electrical methods of heating a stirred tank. The two most common are resistance heating and induction heating. In the former, heat is produced by the direct application of a voltage to a resistor. The resistor material is usually an alloy of nickel and chromium. Electrical resistance heating has the disadvantages of low efficiency, limited life of the resistors, and the inconvenience and expense associated with the removal of insulation to replace burried but resistors.

Induction heating systems work on the principle that disturbances in the molecular structure of material caused by a varying magnetic field, produce heat. Induction heaters can be added to the vessel which is already installed. This can be placed outside the insulation on the vessel. The initial cost of induction heating system is quite low. In addition, they are extremely reliable and require almost no maintenance. However, all electrical heating systems tend to have high operating costs. This may be offset by the following advantages: safety, convenience, cleanliness, precision and ease of control and no possibility of contaminating the process liquid.

1.A.2 Indirect Systems

In these systems, carrier fluids are used to transport heat to the process. The most widely used heat transport fluids are steam and water. The principle disadvantage is the high pressure involved in high temperature systems. Water in its natural state is never pure. It frequently contains dissolved materials which decrease in solubility with increasing temperature. This may result in the formation of scale over heat transfer areas and could lead to a decrease in heat transfer rate. Water may also contain corrosive and foam-producing substances. A further disadvantage of water is that in cold weather, the water may freeze when the system is not in use. Since water expands in volume on freezing, serious demage to equipment can result.

Other fluids commanly used to transport heat are mercury, molten salt mixtures, mineral oils and a number of organic compounds having a variety of trade names. These organic compounds are high boiling materials so that the heat transfer systems can be operated at low pressures. Both liquid and vapor phase systems are used.

In liquid systems, the heat transferred is from sensible heat. The faster the liquid is pumped through the system, the less is its change in temperature over the heat transfer surface and the more uniform is the heating or cooling.

In vapor systems, the heat transferred is from latent heat. Since all the heat transfer takes place at the saturation temperature, the entire transfer surface is at a uniform temperature.

A variety of heating systems used differ from the basic systems. In general, heat transfer coefficients are better for condensing vapor systems than for liquid systems.

In this investigation an indirect liquid heat transfer system was used. Water was carrier fluid to transport heat to the system.

1.B EQUIPMENT AND OPERATION IN LIQUID MIXING

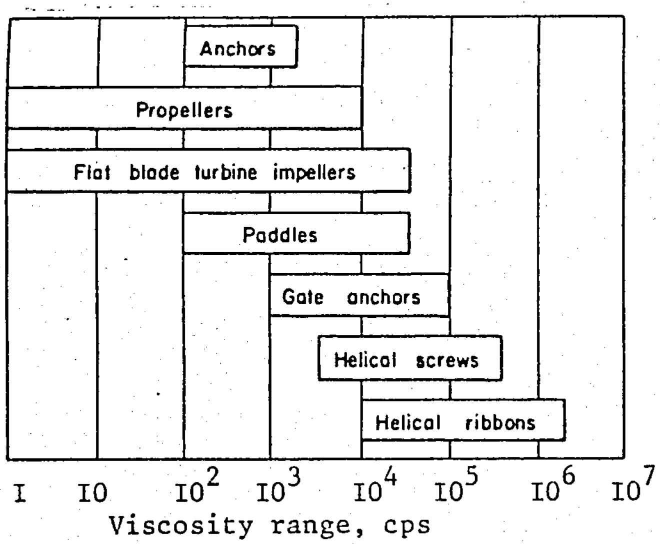
Numerious types of liquid mixing equipment are available for use in chemical processing. The theoretical development of liquid mixing has been slow, and in absence of specific design information, equipment types quite needlessly multiplied during the years. All liquid mixing systems, however, have three factors in common: liquid(s) being mixed, a vessel to confine the liquid(s) and a mechanical device to generate turbulance within the system.

The classification of mixing equipment is usually made on the basis of liquid viscosity since viscosity is a prime contributor to the forces tending to dampen flow through a mixing system. Figure 1.1 shows the recommended viscosity ranges for a number of common agitator types [1].

1.B.1 Turbines and Propellers

For mixing low-to-medium viscosity liquids the flat blade turbine or marine type propeller is recommended. These are general purpose agitators and can be used under a variety of processing conditions. One of the most common turbines is the six blade flat blade, disk mounted type shown in Figure 1.2. A large variety of turbine agitators are available which are modifications of the flat blade design. The disk mounted curved blade turbine (Figure 1.3) and the hub mounted curved blade turbine (Figure 1.4) are useful where the general characteristic of the flat blade type are desired but at a lower shear.

Another modification of the flat blade design is the pitched blade hub mounted turbine (Figure 1.5) with straight blades set at less than 90°C from the horizontal. This design provides reduced



FigureI-I. Viscosity ranges for agitators.

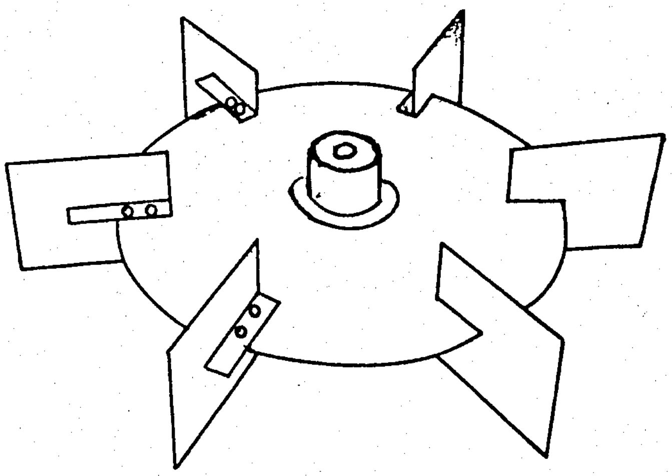


Figure I-2. Six blade flat blade turbine with removable blades.

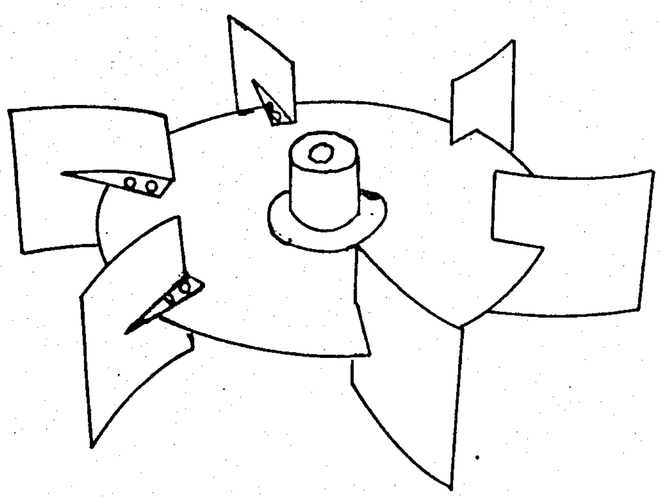


Figure I-3. Disk mounted curved blade turbine.

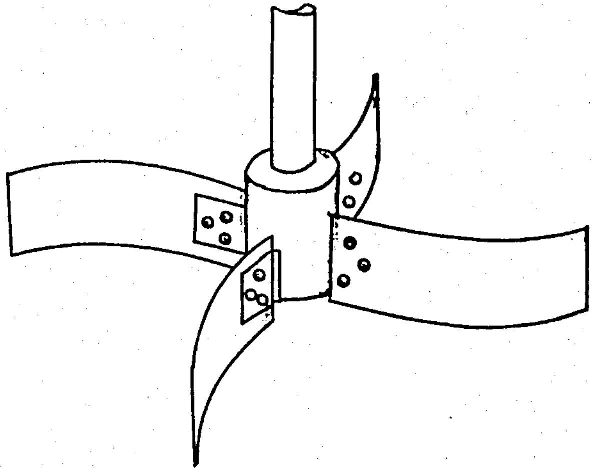


Figure I-4. Hub mounted curved blade turbine.

power requirements and is useful when mixing liquids having a high-gravity solids content. Turbine impellers are made either as single piece castings or in more than one piece. The letter are used for entry into vessels having narrow openings.

A common marine propeller has 3 blades, with a blide pitch equal to the propeller diameter. The marine propeller is shown in Figure 1.6.

The 6 blade flat blade turbine and the marine propeller may be mounted in a vessel in various positions. For general processing service, it is recommended that these agitators be mounted 1 impeller diameter from the tank bottom and have diameters 1/3 of the tank diameter.

Agitators are used to produce flow and, subsequently, turbulence in a liquid mass. Each type of agitator causes high velocity liquid to flow through a vessel in a specific path, referred to as a flow pattern. Flat and curved blade turbines, mixing low or moderate viscosity liquids, produce radial flow patterns when used in a baffled vessel. Radial flow, shown in Figure 1.7A is primarily perpendicular to the vessel wall.

The marine type propeller and pitched blade turbine produce axial flow patterns when centered in a baffled vessel containing low or moderate viscosity liquids. Axial flow, shown in Figure 1.7B is primarily flow parallel to the tank wall.

If either the marine propeller or any of the impeller agitators are used in an unbaffled vessel containing low viscosity liquid(s), vortexing develops. The liquid swirls in the direction of the agitator rotation, causing a drop in liquid level around the agitator shaft. Vortexing increases with impeller speed until eventually the vortex passes through the agitator. The mixing efficiency of vortexing systems is usually lower than for geometrically similar nonvortexing systems.

1.B.2 Paddle Agitators

Paddles are low speed, large blade area agitators, which function by pushing or carrying liquid in a circular path around the vessel. No high speed liquid streams are produced as with turbines, and very little top-to-bottom turnover takes place unless baffles are placed in the vessel and multiple paddles are used. Unbaffled paddles operating in low viscosity liquids produce severe vortexing, even at moderate Reynolds numbers. This leads to inefficient mixing. Since paddles do not mix by high velocity streams, they are well suited for high viscosity service.

Modified versions of the basic 2 blade paddle are available. The choice depends on the viscosity of the liquid and the degree of shear required.

1.B.3 Anchor Agitators

Anchor agitators have been sucessfully used in the batch mixing of liquids having viscosities approaching 100,000 cp Uhl [2] compared the relative effectiveness of an anchor to that of large paddles and turbines operating in viscous fluids. At 40 rpm, the anchor adequately mixed 40,000 cp liquid, as compared to a maximum of 15,000 cp for the turbine and paddle agitators. The anchor agitator is generally slow moving, large surface area device; in close proximity to the vessel wall. For heat transfer applications, wall scrappers are utilized, which prevent the built-up of a stagnant film between the anchor and the vessel wall. For liquids of low viscosity (100-1000 cp) the plain horseshoe type anchor Figure 1.8A provides adequate agitation. As viscosity increases, however, cross-members Figure 1.8B or auxiliary paddles Figure 1.8C are requires to overcome viscous drag forces and maintain motion in the core of the liquid mass. For very viscous liquids double motion anchor-paddle combinations are useful. The same effect is obtained when the basic horseshoe anchor is equipped with additional vertical members. This type of agitator is commonly known as a gate type anchor and is shown in Figure 1.9.

It is generally recognized that slow moving agitators with large surface areas are needed to mix and perform other operations in the processing of viscous materials. The inadequacy of high-speed agitators for this task has been effectively demonstrated. The anchor and its modifications occupies the position of the appropriate agitator for materials having consistencies between mobile fluids and extremely high consistency materials which are generally plastic in character.

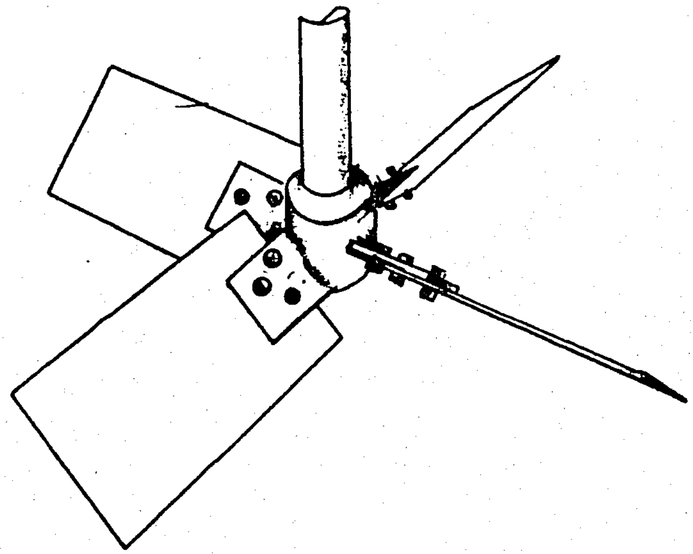


Figure I-5.Hub mounted pitched blade turbine.

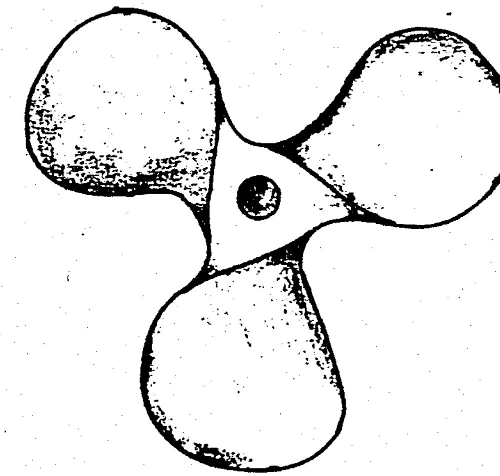


Figure I-6.Marine propeller.

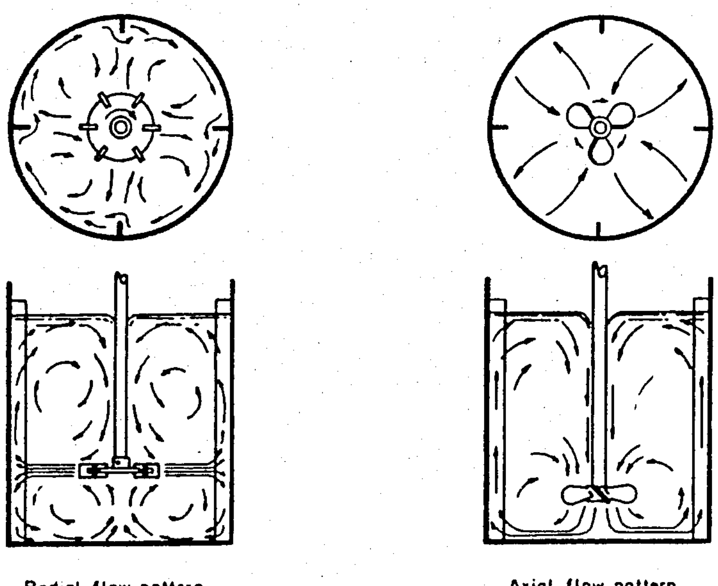


Figure I-7. Radial and axial flow patterns.

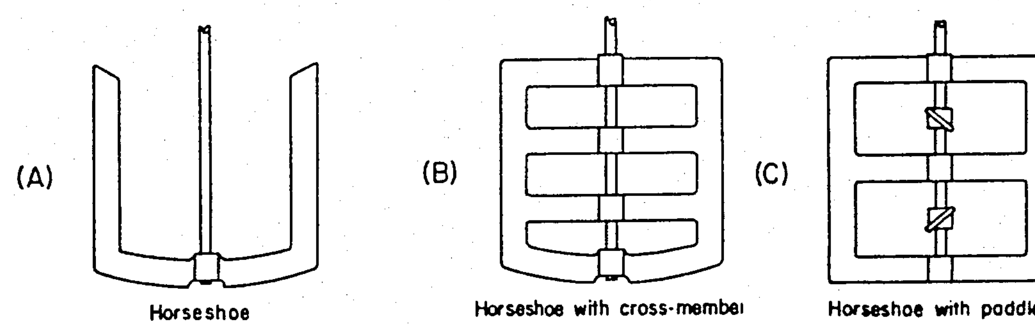


Figure I-8. Anchor agitators.

1.B.4 Helical Screw Agitators

The helical screw agitator Figure 1.10 is an effective device when used in high viscosity liquid(s), since it does not depend on high velocity liquid streams to accomplish mixing.

Helical screws may be obtained in numerious sizes and geometries. All screws, however, are classified on the basis of the following parameters: diameter, pitch, flight number, flight depth and screw length.

The selection of the proper screw for any specific process application is a function of numerious system variables. The screw diameter to tank diameter ratio, the screw pitch to screw diameter ratio, the number of flights and the flight depth each contribute to the overall capabilities of the mixing configuration. The screw length is usually predetermined by processing conditions, since the screw should extend from the tank bottom to the liquid surface.

The screw normally functions by carrying liquid from the vessel bottom to the liquid surface. The liquid is then discharged and returns to the tank bottom to fill the void created when fresh liquid is carried to the surface. Alternatively, screws may be operated in the reverse direction to pull liquid to the bottom of the vessel less power is required in this case.

1.B.5 Double Helical Ribbon Agitators

For extremely high viscosity applications (1,000,000 cp) specialized agitators must be utilized to obtain any degree of

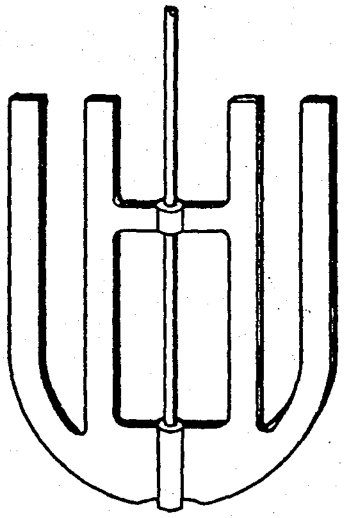


Figure I-9.Gate type anchor agitator.

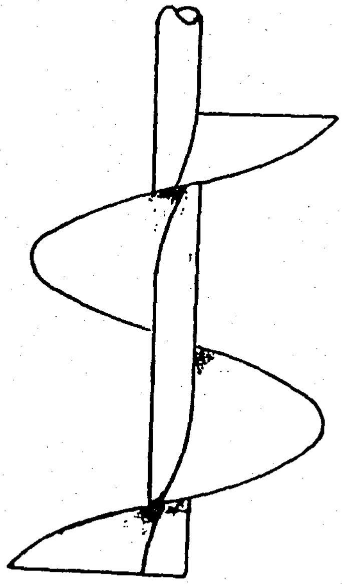


Figure I-10.Helical screw agitator.

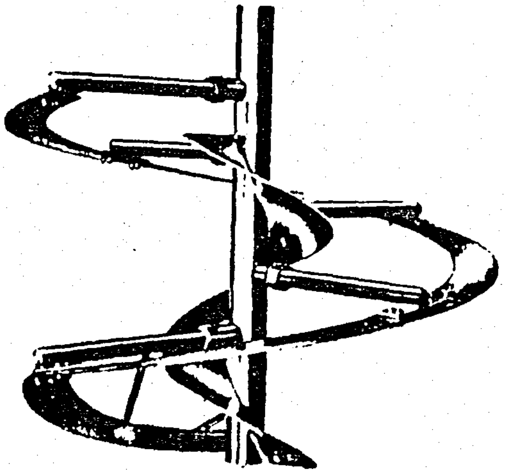


Figure I-11.Helical ribbon agitator.

top-to-bottom turnover. The helical ribbon agitator Figure 1.11 is well suited for ultra high viscosity mixing. Mixing occurs through the forced downward action of the central helix and subsequent bottom-to-top motion brought about by the outer helical ribbon. The helical ribbon gives complete mixing with no stagnant areas. Since the outer ribbon is in close proximity to the vessel wall, the scrapping action increases the heat transfer rate in jacketed tanks.

II. HEAT TRANSFER IN STIRRED TANK SYSTEMS

The heating or cooling of an agitated liquid mass is a common industrial practice. Heat transfer may take place by radiation, conduction or convection, or by a combination of all the three processes. Radiation occurs when energy, in the form of high frequency electromagnetic waves, is emitted from a heat source. Conduction is the transfer of energy between vibrating molecules which remain in a fixed position relative to each other. Convection, both natural and forced, occurs between colliding molecules at different degrees of excitation as they change position and move through a liquid [3].

In a vessel containing an agitated liquid, heat transfer is brought about primarily through conduction and forced convection [4]. The resistance or film, theory conveniently describes this process by

$$\frac{\text{Driving Force}}{\text{Resistance}} = \text{Rate} \tag{2.1}$$

where

Driving Force: Temperature difference, ΔT in °C

Resistance : 1/conductance: 1/U where U is in watt/m^2°C

Rate : Heat flow per unit area, Q/A in watt/m^2

Therefore equation (2.1) can be written as;

$$\frac{\Delta T}{1/U} = Q/A$$

or as, $Q = U\,A\Delta T$.

The overall heat transfer coefficient, U, is determined from a series of five resistances to transfer of heat with internal coils, the coefficient U must be referred to the inner and outer coil surface. The overall heat transfer coefficient, U_o, based on the outside surface of the coil can be written as

$$\frac{1}{U_o} = \frac{1}{h_o} + ff_i + \frac{x}{k_w}\left(\frac{D_{To}}{D_{TAV}}\right) + \frac{1}{h_i}\left(\frac{D_{To}}{D_{Ti}}\right) + ff_{ci} \qquad (2.2)$$

If fouling factors (ff_i, ff_{ci}) are neglected, contributions of the operating variables can be separated into three heat transfer resistances. The outside convective heat transfer coefficient, h_o, lumps together convective and conductive effects in the fluid. This coefficient is usually the limiting resistance and is affected by agitator operation.

In the following sections of this chapter forced convection, inside, outside film coefficient, and methods to obtain individual coefficients will be discussed.

2.A A FORCED CONVECTION

Heat transfer by convection is due to fluid motion. Cold fluid adjacent to a hot surface receives heat which it imparts to the bulk of the cold fluid by mixing with it. Free or natural convection occurs when the fluid motion is not implemented by mechanical agitation. But when the fluid motion is mechanically agitated, the heat is transferred by forced convection. The mechanical agitation may be supplied by stirring, although in most process applications it is induced by circulating the hot and cold fluids at rapid rates on the opposite sides of pipes or tubes. Free and forced convection heat transfer occur at very different rates, the latter being the more rapid and therefore more common. Factors which promote high rates for forced convection do not necessarily have the same effect on free convection.

Forced convection heat transfer is the most frequently employed mode of heat transfer in the process industries. Hot and cold fluids, separated by a solid boundary, are pumped through the heat transfer equipment, the rate of heat transfer being a function of the physical properties of the fluids, of the operating conditions and the geometry of the system. Theoretical analyses of forced-convection heat transfer have been limited to relatively simple geometries and to laminar flow. Analysis of turbulent flow heat transfer have been based upon some mechanistic model and have not generally yielded relationships which are suitable for design purposes. Usually for complicated geometries only empirical relationships are available, and frequently these are based upon limited data and special operating conditions [5,6].

2.B INSIDE FILM COEFFICIENT-INTERNAL COIL

Internal coils should be designed for turbulent flow. For special cases involving viscous heat-transfer fluids, laminar or transition flow may be unavoidable.

Numerous relationships have been proposed for predicting heat transfer for turbulent flow in tubes. A number of observers report data for heating or cooling various fluids with $0.7 < N_{pr} < 700$, for $10.000 < N_{Re} < 120.000$, for $L/D_H \geq 60$. These data [7] for moderate ΔT have been correlated by three types of equations. Dittus and Boelter [8] evaluates all physical properties at the bulk temperature

$$\frac{h_i D_H}{k_b} = 0.023\left(\frac{D_H V_H}{\mu_b}\right)^{0.8}\left(\frac{C_p \mu}{k}\right)_b^{0.4} \tag{2.3}$$

Colburn [9] evaluates all properties, except C_p in the Stanton modules, at the film temperature, $t_f = (t_w + t_b)/2$:

$$\frac{h_i}{C_{p_b} V_H}\left(\frac{C_p \mu}{k}\right)_f^{2/3} = \frac{0.023}{(D_H V_H/\mu_f)^{0.2}} \tag{2.4}$$

Sieder and Tate [10] evaluates all physical properties at the bulk temperature, except μ_w in a viscosity-ratio term:

$$\frac{h_i D_H}{k_b} = 0.023\left(\frac{C_p \mu}{k}\right)_b^{0.33}\left(\frac{D_H V_H}{\mu_b}\right)^{0.8}\left(\frac{b}{\mu_w}\right)^{0.14} \tag{2.5}$$

As pointed out by Colburn [9] the form of the last two equations has several advantages over that of Eq. (2.3).

At a given Reynolds number, heat transfer coefficient of coils, particularly with turbulent flow, are higher than those of long, straight pipes, due to the greater friction. Jaschke [11] found that the results for long straight tubes should be multiplied by a turbulent-flow coil correction factor $(1 + 3.5(D_H/D_c))$. The Sieder-Tate equation for straight pipes, multiplied by a turbulent flow coil correction factor, can be used to calculate the inside convective heat transfer coefficient of coil

$$\frac{h_i D_H}{k_b} = 0.023\left(\frac{C_p}{k}\right)_b^{0.33}\left(\frac{D_H V_H}{\mu_b}\right)^{0.8}\left(\frac{\mu_b}{\mu_w}\right)^{0.14}\left(1 + 3.5\,\frac{D_H}{D_c}\right) \quad (2.6)$$

The transition region lies in the range $2100 < N_{Re} < 10.000$. No simple equation exists for accomplishing a smooth mathematical transition from laminar flow to turbulent flow. Of the relationships proposed, Hausen's equation [12] fits both the laminar and fully turbulent extremes quite well.

$$\frac{h_i D_H}{k_b} = 0.116\left(\left(\frac{D_H V_H}{\mu_b}\right)^{2/3} - 125\right)\left(\frac{C_p \mu}{k}\right)^{1/3}\left[1 + \left(\frac{D_H}{L}\right)^{2/3}\right]\left(\frac{\mu_b}{\mu_w}\right)^{0.14} \quad (2.7)$$

between 2100 and 10.000. It is customary to represent the probable magnitude of coefficients in this region by hand-drawn curves [13].

Normally laminar flow occurs when $N_{Re} < 2100$. Laminar flow heat transfer has been subjected to extensive theoretical study. The energy equation has been solved for a variety of boundary conditions and geometrical configurations. However, true laminar flow heat transfer very rarely occurs. Natural convection effects are almost always present, so that the assumption that molecular conduction alone occurs is not valid. Therefore, empirically derived equations are most reliable.

For circular tubes several relationships are applicable depending upon value of Graetz number, $N_{Gz} = (N_{Re}N_{pr}\ D_H/L)$, where, $N_{Re} = (D_HV_H)/\mu$, $N_{pr} = (C_p\mu/k)$. For $N_{Gz} < 100$, Hausen's [12] equation is recommended:

$$\frac{h_iD_H}{k} = 3.66 + \frac{0.085\ N_{Gz}}{1 + 0.047\ N_{Gz}^{2/3}}(\frac{\mu_b}{\mu_w})^{0.14} \qquad (2.8)$$

For $N_{Gz} > 100$, the Sieder-Tate [10] relationship is satisfactory for small diameters and ΔT's:

$$\frac{h_iD_H}{k} = 1.86\ N_{Gz}^{1/3}(\frac{\mu_b}{\mu_w})^{0.14} \qquad (2.9)$$

A more general expression covering all diameters and ΔT's is obtained by including an additional factor $0.87(1 + 0.015N_{Gr}^{1/3})$ on the right side of Eq. (2.9), where, N_{Gr} =Grashoff number. An equation published by Oliver [14] is also recommended.

In the present study, to calculate film heat transfer coefficient inside the coils, taking into consideration the experimental conditions, the following equations were used; for turbulent flow, Eq. (2.6), for transition region, Eq. (2.7) and for laminar flow, Eq. (2.9).

2.C OUTSIDE FILM COEFFICIENT-INTERNAL COIL

During the past 35 years, there has been considerable investigation of heat transfer coefficients for the agitated side of the coil tank vessels. Many of these heat transfer data are confined to very specific conditions and it is difficult to apply them under conditions other than those from which they were obtained.

Most of the authors present the result of their investigation by an equation of the following form

$$N_{Nu} = C_o . N_{Re}^{A} . N_{pr}^{B} \; V_{is}^{E} \quad (2.10)$$

The constant C_o values differ for various types of mixers and were expressed by a product of new constant C value and dimensionless modul representing the effects of the geometrical mixer parameters so;

$$N_{Nu} = C . N_{Re}^{A} . N_{pr}^{B} . V_{is}^{E} . X_1 . X_2 . \ldots . \quad (2.11)$$

where, $X_1, X_2, \ldots .$ are dimensionless moduli representing the effect of mixer geometry on heat transfer in a mixing vessel.

$N_{Re} = \frac{\rho . N . D_A^2}{\mu}$ is modified Reynolds number (for mixing).

$N_{pr} = \frac{C_p . \mu}{k}$ is the Prandtl number,

$N_{Nu} = \frac{h_o . D_H}{k}$ is the Nusselt number,

$V_{is} = \frac{\mu_b}{\mu_w}$ is the ratio of the process-liquid viscosities at bulk temperatures and at wall temperatures.

The results of more extensive experimental investigations are outlined in this section. Except for the scattered early data of Pierce and Terry [15] and of Rhodes [16], the work of Chilton et al. [17] was the first study to use conventional groups for correlating heat transfer to jackets or coils. Since then, considerable progress in this area has been made despite the many variables required to describe the geometry of a typical agitated system. Known heat transfer data for helical coils are summarized in Table 2.1. The manner of presentation of this indicates both, that there is no overall correlation of the available data, and that there are fragments of information giving the effect of many variables. The correlating equation of each separate work is tabulated in Table 2.2.

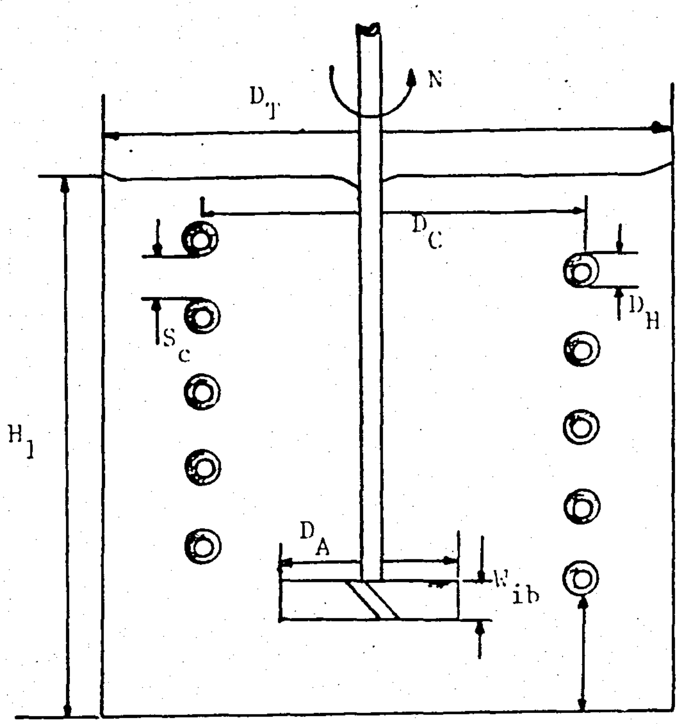


Figure 2-1. Agitated vessel with immersed coil for heat transfer.

TABLE 2.1 - Heat Transfer to Immersed Helical Coils in Agitated Vessels

Impeller			Helical Coil						Vessel		
Investigator	D_A(in)	w_{ib}/D_A	H_c/D_A	Material	D_H(in)	S_c(in)	D_c(in)	H_c(in)	D_T(in)	H_ℓ/D_T	Bottom Type
1) CHILTON et.al	7.2	0.17	0.33	Copper	1/2	1/4	9.60	5.75	12	0.83	Dished
2) PRATT	5.5-14	various	various	Stainless steel and lead	3/4-3.5	0.48-2	7.75	18-28	18-23.5	-	Flat
3) CUMMING and WEST	12	0.17		stainless steel	1.0	1/2	24	23	30	1.0	Dished
4) KRAUSSOLD	20	1.4		-	-	25/32	-	-	40	1.1	Dished
5) OLDSHUE and GRETTON	20-28	0.2		Copper	7/8	7/8	3.15	31.5	48	1	Flat
				Stainless steel	1.75	1.75	34.2	31.5	48	1	Flat
6) SKELLAND and DABROWSKI	36.9	-		Copper	3/4	1.25	13	15	-	H :20"	Flat
7) JHA and RAO	4	$\frac{\text{Baffle width}}{D_A}$ = 0.25		Copper	1/2	-	10	-	14	1.4	Flat

1) [17]
2) [18]
3) [19]
4) [20]
5) [21]
6) [22]
7) [23]

* See Fig. 2.1 for representation of symbols.

TABLE 2.2 - Summary of Correlations

Investigator	Correlation	Range of N_{Re}
1) CHILTON Et al.	$\frac{h_o D_T}{k} = 0.87(N_{Re})^{0.62}(N_{pr})^{0.33}(\mu_b/\mu_w)^{0.14}$	$300 - 4x10^5$
2) PRATT	$\frac{h_o D_T}{k} = 34(N_{Re})^{0.5}(N_{pr})^{0.3}(S_c/H_c)^{0.8}(W_{ib}/D_c)^{0.25}((D_A D_T)/D_H)^{0.1}$	$2x10^4 - 5x10^5$
3) CUMMING and WEST	$\frac{h_o D_T}{k} = 1.01(N_{Re})^{0.62}(N_{pr})^{1/3}(\mu_b/\mu_w)^{0.14}$	$2x10^3 - 7x10^5$
4) KROUSSOLD	$\frac{h_o D_T}{k} = 1.01(N_{Re})^{0.62}(N_{pr})^{1/3}(\mu_b/\mu_w)^{0.14}$	$0.3 - 1x10^5$
5) OLDSHUE and GRETTON	$\frac{h_o D_H}{k} = 0.17(N_{Re})^{0.67}(N_{pr})^{0.37}(D_A/D_T)^{0.1}(D_H/D_T)^{0.5}$	$400 - 1.5x10^6$
6) SKELLAND and DABROWSKI	$\frac{h_o D_H}{k} = 0.345(N_{Re})^{0.62}(D_T/C_p)^{0.27}$	$2.5x10^5 - 10^6$
7) JHA and RAO	$\frac{h_o D_T}{k} = 0.18(N_{Re})^{0.67}(N_{pr})^{0.33}(D_H/D_T)^{-0.48}(D_c/D_T)^{-0.27}(H_c/D_T)^{0.14}$	$1 - 2.5x10^5$

From Table 2.1, the designer can obtain dimensions for geometric similarity. Although Pratt's work offers the choice of more dimensional variables, the different values for some of the exponents in Pratt's equation [18] introduce some question concerning the accuracy obtained by using this relationship directly. Very little of the other work has been directed towards finding the effect of dimensional variations. Cummings-West [19] ran tests under steady-state conditions using six different liquids having widely varying properties. These tests indicated that film coefficients would be the same for a given Reynold number whether one or two turbines were on the shaft. The tests conducted with the pitched-blade turbine instead of retreating-blade turbine showed on approximate 10% reduction in film coefficient. No significant change in the film coefficient resulted from reversing the pitched-blade turbine. It is apparent that only two of the available correlations, Oldshoe's and Skelland's [21,22] indicate the effect of coil tube diameter, 'D_H'. Also, since $D_T >> D_H$ the values of 'h_o' obtained from the same Nusselt number for different correlations, is different. Since the Nusselt number describes heat transfer occurring mainly at the coil, it is more logical to define Nusselt number based on the coil tube diameter, 'D_H', rather than the tank diameter D_T [24]. Of the dimensional parameters, only the effect of D_A, D_T, and to an extent 'D_H' in addition to fluid properties are indicated in Table 2.3. None of these can be considered to be fairly established [2]. It may be remarked that the parameters 'D_H' and 'S_c' have much greater influence on 'h_o'. These affect considerably the flow distribution through and around the coil or the degree of by passing.

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TABLE 2.3 - Comparison of Exponentials of Correlations

Variable	CHILTON et al.	PRATT	CUNNING and WEST	OLDSHUE and GRETTON	SKELLAND and DABROWSKY	JHA and RAO
D_A	1.24	1.20	1.24	1.43	1.24	1.34
N	0.62	0.5	0.62	0.67	0.62	0.67
D_T	-1.0	-0.9	-1.0	-0.6	0.27	-0.39
D_H	-	-0.3	-	-0.5	-1.0	-0.48
S_c	-	0.8	-	-	-	-
μ^*/μ_w	0.14	0.14	-	0.14	0.14	0.14

*Most have assumed this in accordance with Sieder and Tate.

The influence of a number of other factors can be expressed qualitatively. At lower speeds the effect of agitation can be overshadowed by free convection [2], and at increasingly higher speeds the heat transfer rates will level off. The impeller blade length and width, obviously affect the area of shear, turbulence, hence degree of mixing. This consequently is revealed as nonuniformities is temperature. The parameters H_{ib}, H_{ℓ}, D_c again affect the degree of turbulence and mixing, thus influencing 'h_o'. The influence of other factors, such as type of impeller, number of impellers, and other factors on 'h_o' can not be established and the need for more data is obvious.

2.D METHODS TO OBTAIN INDIVIDUAL FILM COEFFICIENTS

Values of the individual film coefficients are obtained experimentally by one of three methods:

1. Use of modified Wilson plot [25,19,2]
2. Measurement of the temperature of the heat transfer barrier by imbedded thermocouples, [17,26,21]
3. Measurement of mechanical energy losses and use of momentum and heat transport analogies [27,28].

The use of the Modified Wilson plot [29] bears further discussion. In this part the Modified Wilson plot which was used in this investigation will be discussed in detail.

a) Case I (determination of inside film coefficient, h_i)

For the case where outside resistance of coil is controlling, and when conditions of flow and temperature inside the coil do not change appreciably, it can be shown that Eq.(2.2) reduces to

$$\frac{1}{U_o} = \beta + \frac{1}{h_o} \qquad (2.12)$$

For a given vessel and coil geometry, it can be recognized that h_o is the some way dependent on degree of mixing, hence speed of the agitator. Thus for above conditions, it is satisfactory to say that [30]

$$h_o = K\,N^{\alpha}$$

Experimental observations seem to indicate that α is 0.62 [19] so Eq. (2.12) becomes

$$\frac{1}{U_o} = \beta + \frac{1}{K\,N^{0.62}} \qquad (2.13)$$

Thus a plot of $1/U_o$ vs $1/N^{0.62}$ will be linear with a slope of 1/K and an intercept of β, after determining β and using its definition

$$\beta = \frac{1}{h_i}\,\frac{A_o}{A_i} + \frac{x}{k}\,\frac{A_o}{A_m} \quad \text{(constant)} \qquad (2.14)$$

such that k and h_i do not vary appreciably, one can evaluate "h_i" as all the remaining terms are known.

b) <u>Case II</u> (determination of outside film coefficient, h_o)

For the case where resistance of the coil is controlling, and when degree of mixing, and temperature outside the coil do not change appreciably, it can be shown that [30]

$$\frac{1}{U_i} = \gamma + \frac{1}{h_i} \tag{2.15}$$

For a given coil geometry, it can be imagined that "h_i" like the friction factor inside the coil must in the some way be related to the flow pattern, hence the velocity of flow of the fluid through the coil. Thus for this conditions it can be assumed that

$$h_i = K'V^{\alpha'}$$

Experimental observations seem to indicate that α' is 0.8 and for fully developed turbulent flow then Eq. (2.15) becomes

$$\frac{1}{U_i} = \gamma + \frac{1}{K'V^{0.8}} \tag{2.16}$$

Thus a plot of $1/U_i$ vs $1/V^{0.8}$ will be linear with a slope of $1/K'$ and intercept of γ

$$\gamma = \frac{1}{h_o}\frac{A_i}{A_o} + \frac{x}{k}\frac{A_i}{A_m}\ , \tag{2.17}$$

h_o, and k do not vary appreciably. Thus h_o can be evaluated.

In the present study the Wilson graphical method was used to calculate individuals coefficients from the experimental overall coefficients.

III. MATHEMATICAL MODELLING

In this chapter mathematical models were developed for a continuous stirred single tank and for two stirred tanks in series respectively. Only the original differential equations, the boundary conditions and final solutions have been presented in this chapter. The details on solutions are explained in Appendix II.

3.A MATHEMATICAL MODELLING FOR A SINGLE CONTINUOUS STIRRED TANK

For the single continuous stirred tank, where the flow of cold water is in the tank side and that of hot water is in the coil side, counter current flow operation may be performed.

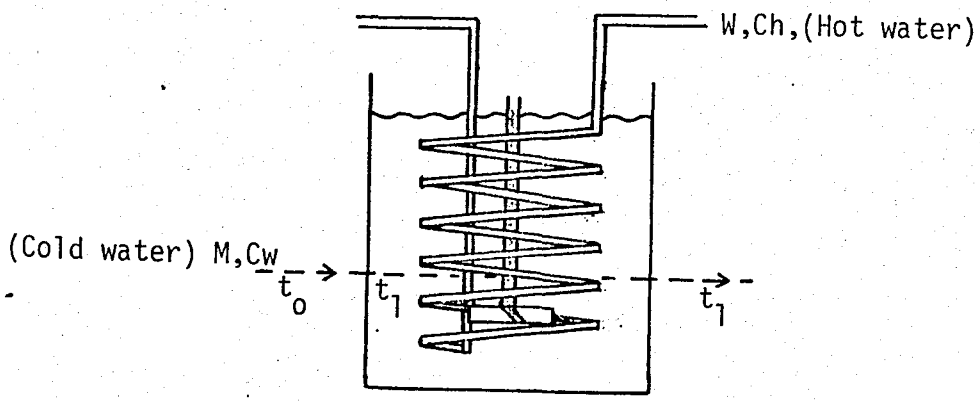


Figure 3.1 - Single tank

Then, the heat balance for the tank shown in Figure 3.1 is as follows

$$\{\text{Input}\} \quad - \quad \{\text{Output}\} \quad = \quad \{\text{Accumulation}\}$$

$$WC_h\rho_hT_1 - WC_h\rho_hT_2 + (MC_w\rho_wt_o - MC_w\rho_wt_1) = VC_w\rho_w(dt_1/d\theta) \quad (3.1)$$

where;

M : Cold water flowrate

W : Hot water flowrate

C_h: Hot water heat capacity

U : Overall coefficient of heat transfer

A : Heat transfer area of coil

V : Volume of the tank

C_w: Cold water heat capacity

T_1: Hot water inlet temperature

T_2: Hot water exit temperature

t_o: Cold water inlet temperature

t_1: Cold water exit temperature

ρ_h: Hot water density

ρ_w: Cold water density

θ : Time

Assuming proper agitation, (i.e. uniform temperature in the tank, t_1) the heat transfer rate equation for the tank is

$$\frac{U_1A(T_2 - T_1)}{\ln \dfrac{T_2 - t_1}{T_1 - t_1}} = WC_h\rho_h(T_1 - T_2)$$

this equation simplifies to

$$\frac{T_2 - t_1}{T_1 - t_1} = \exp[- \frac{U\ A}{WC_h\rho_h}] = \alpha_1 \text{ (Alpha}_1\text{)} \qquad (3.2)$$

Using the following initial condition

at $\quad \theta = 0 \qquad t_1 = t_{1s} \qquad$ (After reaching a steady-state)

the final solution is

$$t_1 = [t_{1s} - \frac{WC_h\rho_h(1-\alpha)T_1 + MC_w\rho_w t_o}{MC_w\rho_w + WC_h\rho_h(1-\alpha)}]\exp^{-[\frac{MC_w\rho_w + WC_h\rho_h(1-\alpha)}{VC_w\rho_w}]}$$

$$+ \frac{WC_h\rho_h(1-\alpha)T_1 + MC_w\rho_w t_o}{MC_w\rho_w + WC_h\rho_h(1-\alpha)} \qquad (3.3)$$

where, T_1 and t_o are known temperatures, and t_1 and T_2 can be calculated.

3.B MATHEMATICAL MODELLING FOR TWO STIRRED TANKS IN SERIES

Consider the system, where cold water at temperature t_o is fed to tank I where it is well-stirred in contact with heating coils. The continuous discharge from this tank at temperature t_1 flows into stirred tank II and leaves tank II at temperature t_2. Heating water at temperature T_1 flows into the coil of the tank II and then leaves tank II at temperature T_2 enter the coil of the first tank. Finally the hot water is at temperature, T_3 as it leaves the coil of tank I.

Symbols used in the modelling are similar to those of the single tank, the only difference being that subscripts 1 and 2 indicate the properties which belong to tank I and tank II respectively.

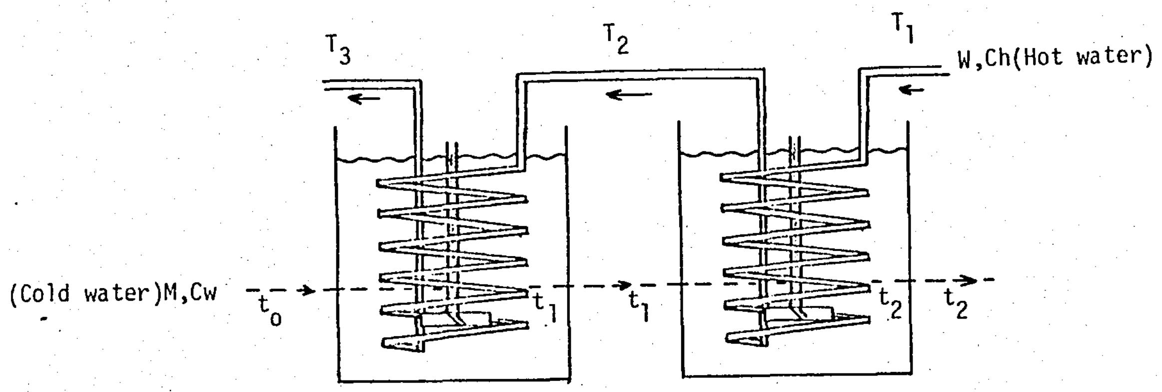


Figure 3.2 - Two tanks in series

Then the heat balances for the two tanks in series shown in Figure 3.2 are as follows;

$$\text{TANK I: } WC_h\rho_h(T_2-T_3) - MC_w\rho_w(t_1-t_o) = VC_w\rho_w \frac{dt_1}{d\theta} \qquad (3.4)$$

$$\text{TANK II: } WC_h\rho_h(T_1-T_2) - MC_w\rho_w(t_2-t_1) = VC_w\rho_w \frac{dt_2}{d\theta} \qquad (3.5)$$

Assuming proper agitation (i.e. uniform temperature in tank I, t_1 and in tank II, t_2) the heat transfer rate equations for the tanks I and II, are

$$\text{TANK I} \quad \frac{T_3 - t_1}{T_2 - t_1} = \exp[-\frac{U_1A}{WC_h\rho_h}] = \alpha \quad \text{(Alpha)} \qquad (3.6)$$

TANK II $$\frac{T_2 - t_2}{T_1 - t_2} = \exp[-\frac{U_2 A}{W C_h \rho_h}] = \beta \qquad \text{(Beta)} \tag{3.7}$$

Using systematic elimination technique [31] the amount of algebra involved may be reduced to a minimum. These four equations are solved simultaneously.

Initial conditions are;

at $\theta = 0$ $\quad t_1 = t_{1s}$, $\quad t_2 = t_{2s}$ (After reaching a steady-state)

Final solutions are

$$t_1 = \frac{V}{M}[m_1 A e^{m_1 \theta} + m_2 B e^{m_2 \theta}] + [\frac{W C_h \rho_h}{W C_w \rho_w}(1 - \beta) + 1] *$$

$$(A e^{m_1 \theta} + B e^{m_2 \theta} + CP) + [\frac{W C_h \rho_h}{M C_w \rho_w}(\beta - 1)]T_1 \tag{3.8}$$

and

$$t_2 = A e^{m_1 \theta} + B e^{m_2 \theta} + CP \tag{3.9}$$

where;

$$CP = \frac{M C_w \rho_w t_o + (W C_h \rho_h - W C_h \rho_h \alpha\beta + \frac{W^2 C_h^2 \rho_h^2}{M C_w \rho_w} - \frac{W^2 C_h^2 \rho_h^2 \alpha}{M C_w \rho_w} - \frac{W^2 C_h^2 \rho_h^2 \beta}{M C_w \rho_w} + \frac{W^2 C_h^2 \rho_h^2 \alpha\beta}{M C_w \rho_w})T_1}{M C_w \rho_w + W C_h \rho_h - W C_h \rho_h \alpha\beta - \frac{W^2 C_h^2 \rho_h^2 \alpha}{M C_w \rho_w} + \frac{W^2 C_h^2 \rho_h^2 \alpha\beta}{M C_w \rho_w} - \frac{W^2 C_h^2 \rho_h^2 \beta}{M C_w \rho_w} + \frac{W^2 C_h^2 \rho_h^2}{M C_w \rho_w}}$$

$$m_{1,2} = \frac{-BP \pm \sqrt{BP^2 - 4DP}}{2}$$

$$BP = \frac{2 W C_h \rho_h}{V C_w \rho_w} + \frac{2M}{V} - \frac{W C_h \rho_h}{V C_w \rho_w} - \frac{W C_h \rho_h}{V C_w \rho_w}$$

$$DP = \frac{M^2}{V^2} + \frac{MWC_h\rho_h}{V^2C_w\rho_w} - \frac{W^2C_h^2\beta}{V^2C_w^2\rho_w^2} + \frac{W^2C_h^2\rho_h^2}{V^2C_w^2\rho_w^2} + \frac{W^2C_h^2\rho_h^2\alpha\beta}{V^2C_w^2\rho_w^2} - \frac{W^2C_h^2\rho_h^2\alpha}{V^2C_w^2\rho_w^2} - \frac{WMC_h\rho_h\alpha\beta}{V^2C_w\rho_w}$$

$$B = \frac{t_{1s} + \left(\frac{WC_h\rho_h}{MC_w\rho_w} - \frac{WC_h\rho_h\beta}{MC_w\rho_w}\right)T_1 + \frac{V}{M}m_1 CP - \left[\frac{WC_h\rho_h}{MC_w\rho_w}(1-\beta) + \frac{V}{M}m_1 + 1\right]t_{2s}}{\frac{V}{M}(m_2 - m_1)}$$

$$A = t_{2s} - B - CP$$

3.C DESCRIPTION OF THE COMPUTER PROGRAMS

Computer programs for both the single tank system and the two tanks in series were prepared using the analytical model developed in part (3.A) and (3.B) to facilitate the calculation of steady-state and unsteady-state temperatures and of heat transfer coefficients. Each program contains a main program and four subprograms which calculate physical properties of water (Appendix IV).

The program flowcharts are given in Figure 3.3 for the single tank and in Figure 3.4 for two tanks in series. Symbols used are given in Appendix III.

Inlet temperatures and flowrates of hot and cold water are given as data input SI units have been used in both programs, as well as in the data and the results.

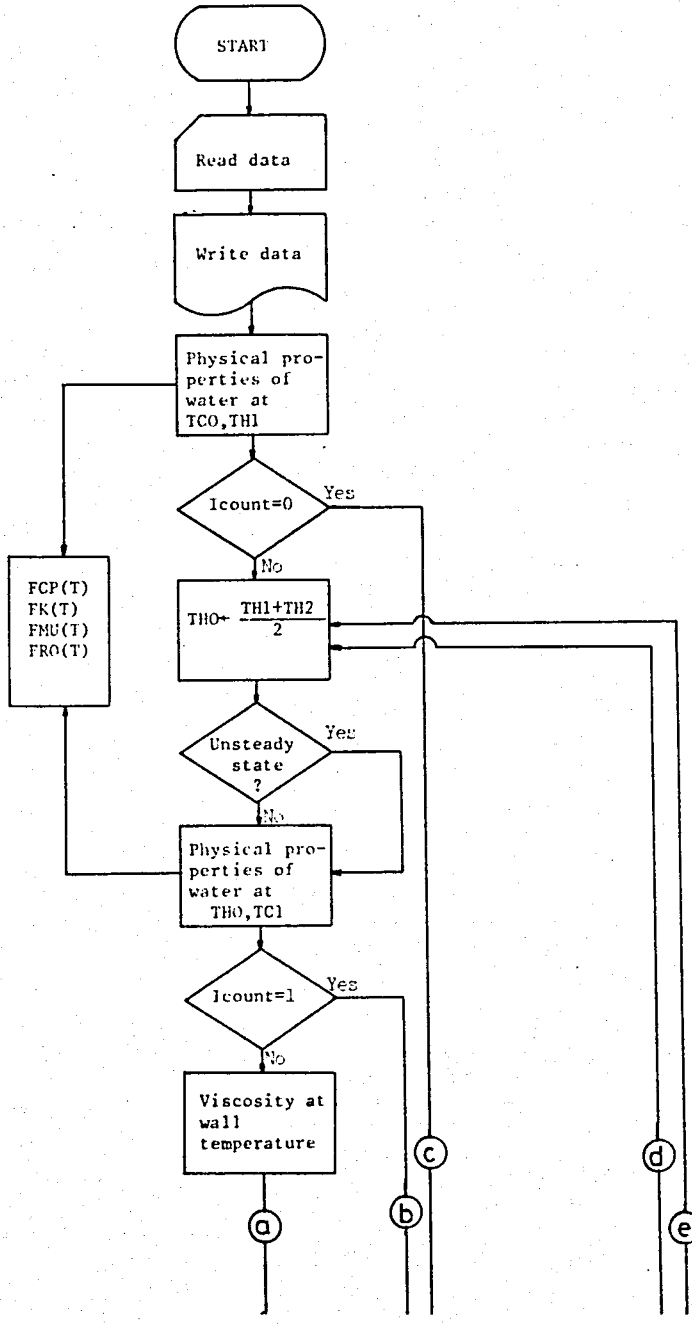
In both programs, data are read and written first. Time is taken large enough to obtain steady-state temperatures and then physical properties of water (i.e. C_p, μ, ρ, k) are evaluated at inlet hot and cold water temperatures. New temperatures are calculated until the desired convergence is obtained. These temperatures are written as steady-state temperatures. Secondly, using the steady-state values as initial values, transient temperatures are calculated at thirty second time intervals.

These programs calculate the film heat transfer coefficient inside the coils, using the following equations for turbulent flow Eq. (2.6), for transition region, Eq. (2.7), for laminar flow, Eq. (2.9). They also make use of the Cumming-West's correlation [Table 2.2, Eq. 3], but geometry factor "1.40" to calculate outside film heat transfer coefficient.

In the "Single Tank" program, Equations 3.2 and 3.3 are used to calculate temperatures.

In the "Two Tanks in Series" program, Equations 3.6, 3.7, 3.8 and 3.9 are used to calculate unknown temperatures.

Figure 3-3.Flow chart of single tank.



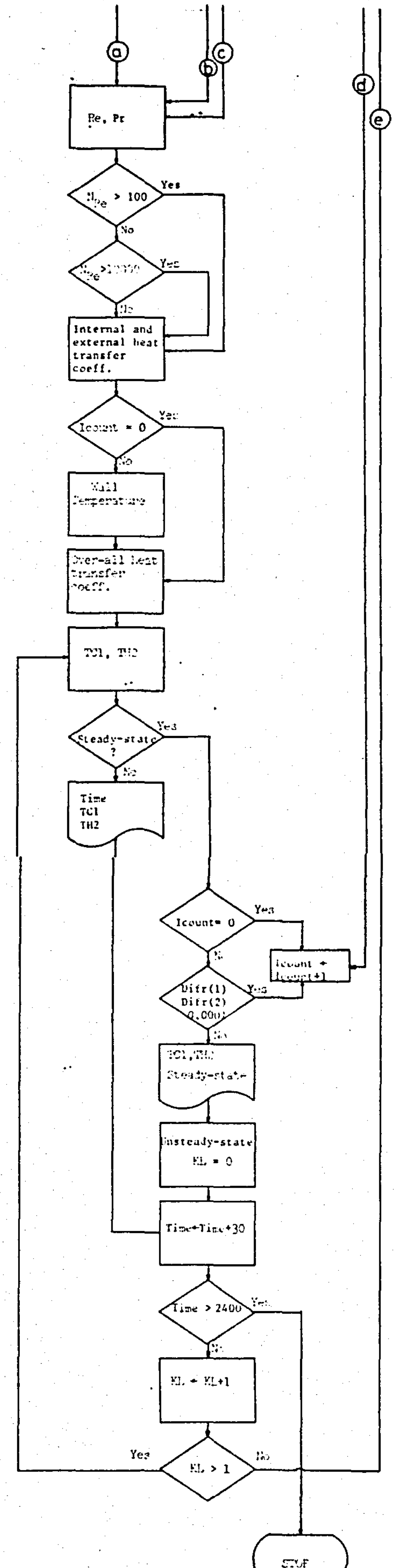
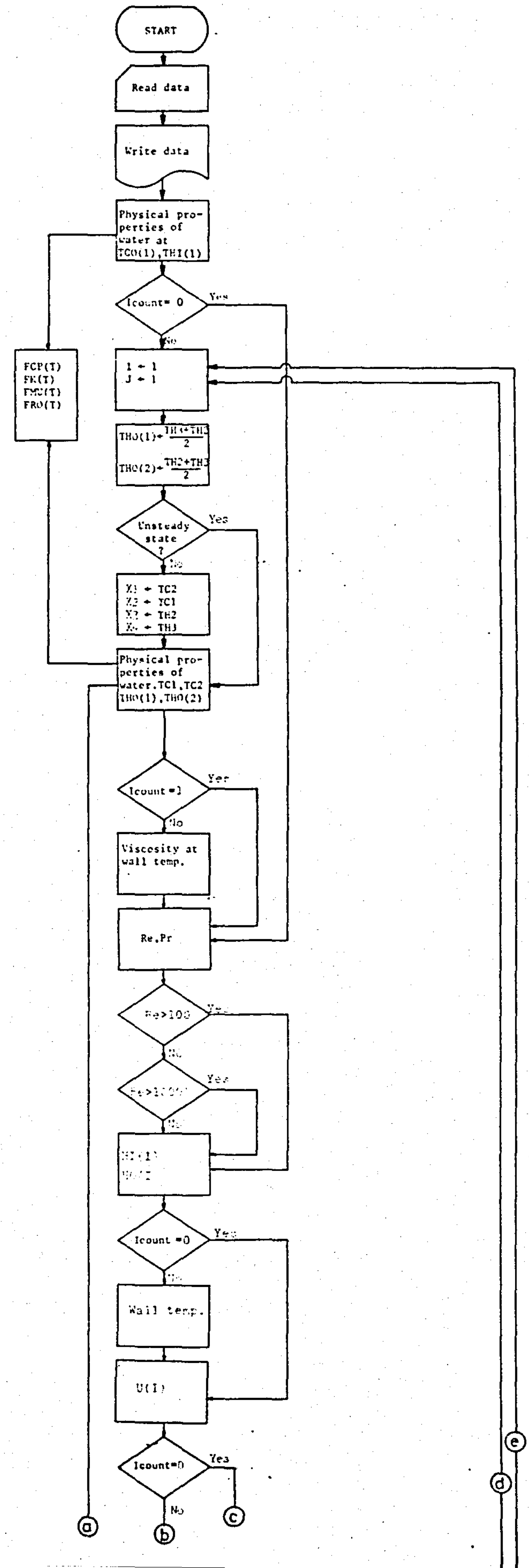
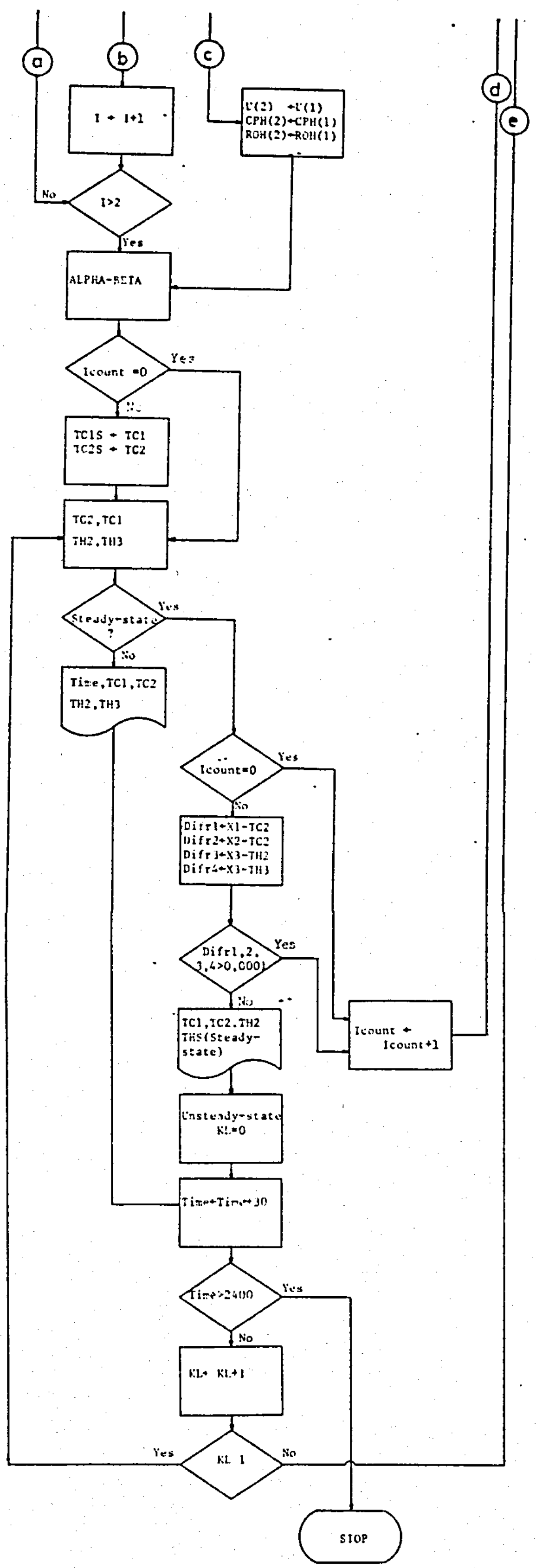

a
b
c
d
e
Re, Pr
Yes
No
Internal and external heat transfer coeff.
Yes
No
Over-all heat transfer coeff.
Yes
Steady-state ?
No
Time
TC1
TH2
Icount= 0
Yes
Unsteady-state
KL = 0
Time > 2400
Yes
KL > 1
No

Figure3-4.Flow chart of two tanks in series.




a
b
c
d
e
I ← I+1
V(2) ←V(1)
CPH(2)←CPH(1)
ROH(2)←ROH(1)
No
I>2
Yes
ALPHA-BETA
Icount =0
Yes
No
TC1S ← TC1
TC2S ← TC2
TC2,TC1
TH2,TH3
Steady-state ?
Yes
No
Time,TC1,TC2
TH2,TH3
Icount=0
Yes
No
Difr1←X1-TC2
Difr2←X2-TC2
Difr3←X3-TH2
Difr4←X3-TH3
Difr1,2,3,4>0,0001
Yes
No
TC1,TC2,TH2
THS(Steady-state)
Icount ← Icount+1
Unsteady-state
KL=0
Time←Time+30
Time>2400
Yes
No
KL← KL+1
Yes
KL 1
No
STOP

IV. EXPERIMENTAL WORK

In this chapter experimental equipment and experimental procedure are described.

4.A EXPERIMENTAL EQUIPMENT

The experimental set-up used in this study consisted of two dimensionally similar tanks, coils, stirrers, a number of thermocouples, a digital thermometer, pumps, a hot and cold water reservoir and heaters as shown in Figure 4.1 for single tank and Figure 4.2 for two tanks in series. The connections were provided by specially insulated pipes.

4.A.1 Tanks

Each galvanized tank having 20.0±0.1 cm (7.9 in) inside diameter, was cylindrical, flat bottomed and capable of holding 4.08×10^{3} cm^{3} (1.08 ga). Also in front of the each tank, there was a glass liquid level indicator pipe.

4.A.2 Coils

The coils were made of clean copper tubing and were fixed by means of corks to the lids of the tanks so that they stood firmly inside the vessels. The coiling was circular and the gap between individual turns of coils was sufficiently great to allow for free circulation of liquid over the complete surface of the tubing. Each gap was 0.635±0.1 cm (0.250 in). The copper tubes used were 0.635±0.01 cm (0.250 in) outer diameter and 0.470±0.01 cm (0.185 in) inside diameter.

4.A.3 Stirrers

Agitation was supplied by flat blade turbine impeller, 7.99±0.01 cm (3.15 in) in diameter. Each impeller contained six blades, each being 1.99±0.01 cm (0.82 in) in width. The impellers were placed at a height of 6.0±0.2 cm (2.4 in) from the bottom of the vessel.

4.A.4 Thermocouples

Temperature measurements were measured using iron-constantan thermocouples, 0.10 cm in diameter. In order to minimize response time, thermocouple junctions were inserted into water without protecting tubes. In order to prevent thermocouples from the corrosive effect of water, first, all thermocouple junctions were cleaned with a kind of detergent, known as Lissapol NX, to remove oil and other dirts, then coated with nail lacquer.

Iron-constantan is the most widely used of all thermocouples.

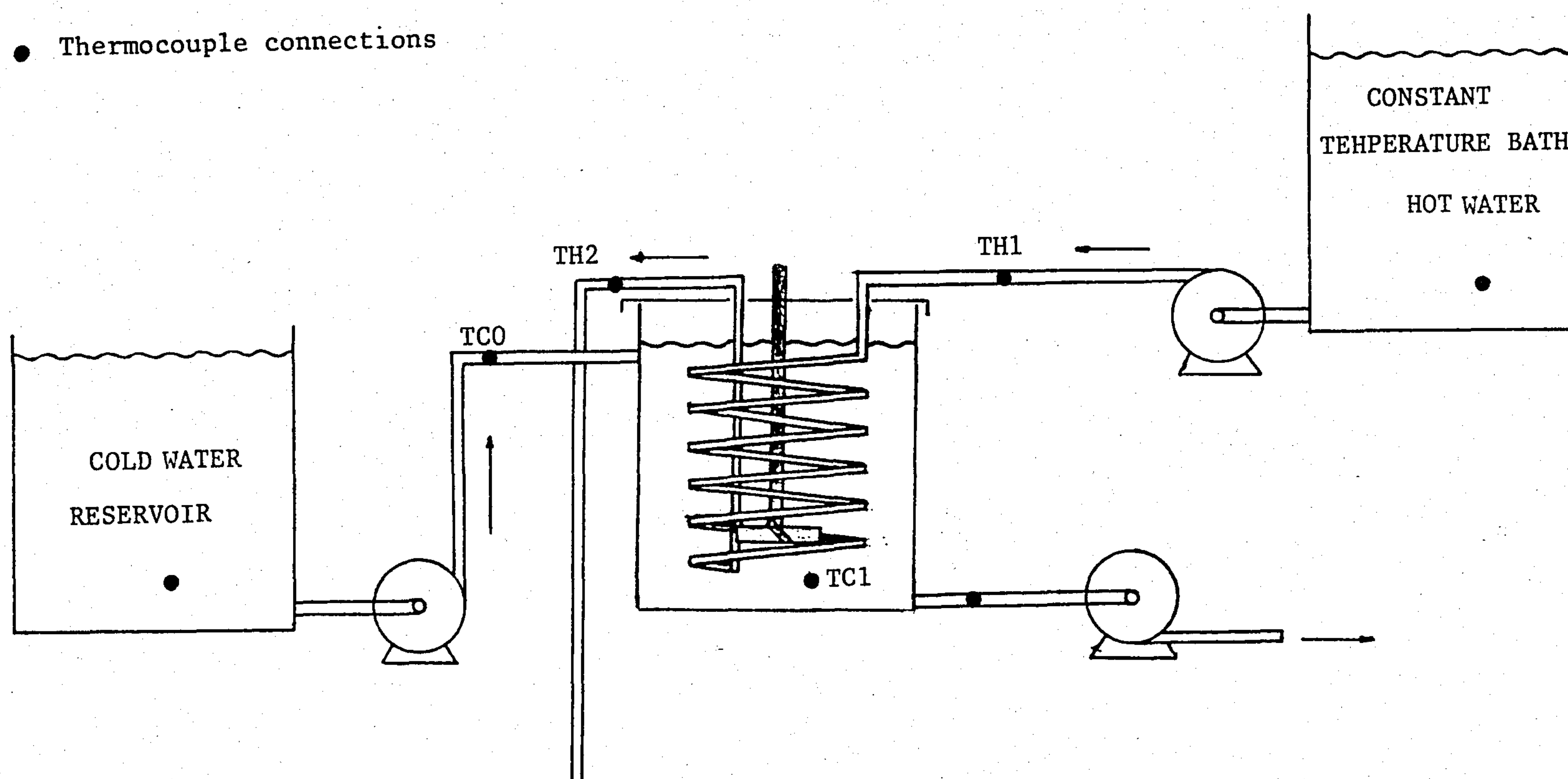


Figure 4-I.Experimental set up single tank.

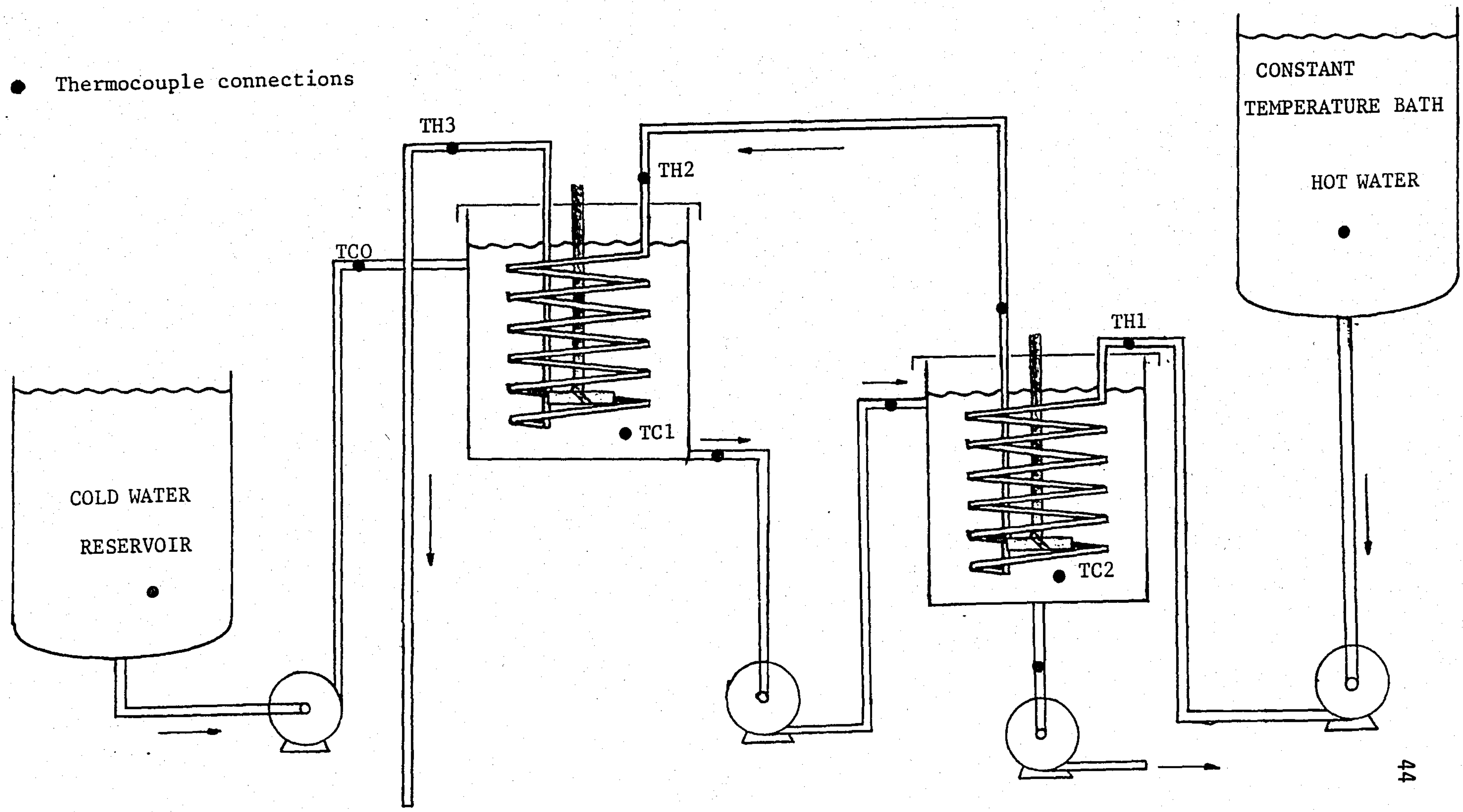


Figure 4-2. Experimental set up two tanks in series.

It gives a higher emf at a given temperature than any of the other common couples, and is the least expensive. Their usual temperature range of operation is -200 to 750°C (-300 to 1400 °F).

4.A.5 Digital Thermometers

Temperature measurements were directly read out by means of a digital thermometer which had twelve separate thermocouple connections. Some technical specifications of this instruments are given below.

Line voltage	: 220 V AC ±15%, 48, 52 Hz
Operating temperature	: -10 to +50°C
Power consumption	: 4 VA
Measurement sensitivity	: ±0.1% (full scale)
Break protection	: If the sensor probes are open the display is blanked.

4.A.6 Hot Water Reservoir

The hot water reservoir was a rectangular galvanized tank, approximately 50 cm long, 25 cm wide and 50 cm high. It was insulated carefully with glass wool and two layers of nylon were wrapped around it.

4.A.7 Cold Water Reservoir

A 50 lt plastic container was used as cold water feed tank. In order to prevent variation of the head of pump connected to this container, liquid level in the container was kept constant throughout the experiment.

4.A.8 Heaters

Two heating mantles were placed inside the hot water reservoir. One, had a resistance thermometer which could be set at a desired temperature (CENCO, 1010 W, 110 V), the other an electrical resistance (2500 W, 220 V). The temperature was also controlled by an inserted thermocouple.

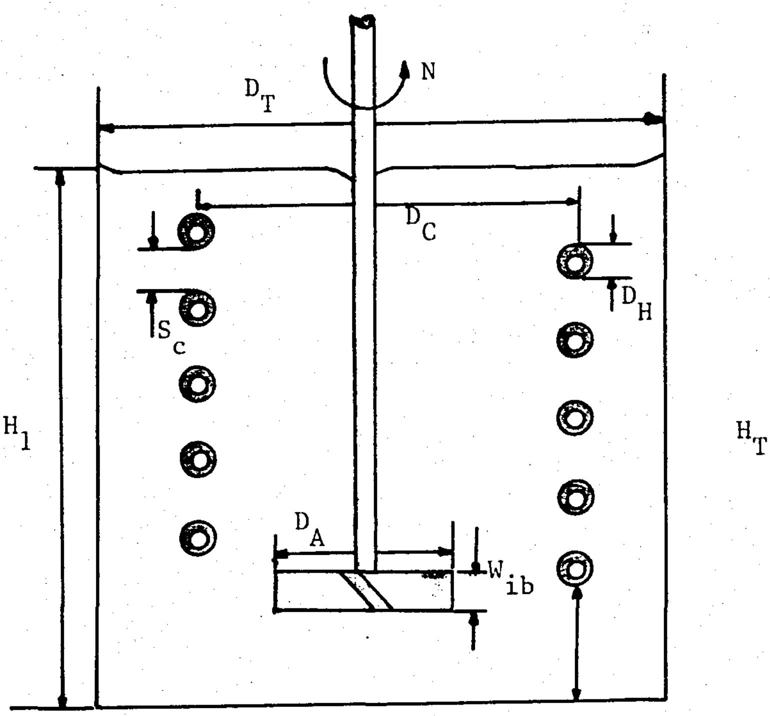
4.A.9 Rotary Pumps

Two types of rotary pump were used, a 50 W,200 U/min pump and a 90 W, 2000 U/min pump to feed hot and cold water streams.

Dimensions of the tank system used in the experimental work are shown in Figure 4.3.

4.B EXPERIMENTAL ARRANGEMENT

Two types of arrangements were used for the experiments. Firstly, single tank arrangements as shown in Figure 4.1 and secondly two tanks in series, Figure 4.2, are described below.



D_T : 20.0± 0.1 cm	D_H : 0.635±0.01 cm	W_{ib} : 1.92±0.01 cm
H_T : 24.0 ± 0.1 cm	D_A : 7.99 ±0.01 cm	H_1 : 17.0±0.1 cm
D_c : 16.0 ±0.2 cm	S_c : 0.635±0.1 cm	

Figure 4-3. Dimensions of the tank system.

The single tank was insulated by glass wool first and wrapped by nylon sheets in order to prevent insulater from getting wet. Flat blade turbine impellers were mounted on the shaft coaxial with the tanks. The lower edge of each agitator was placed at a height of 6.0±0.2 cm (2.4 in) from the bottom of the vessel. Agitator speed was set at the desired speed by means of the speed button on a Heidolph stirrer whose stirring speed could be changed over a range of 45 to 2000 rpm. This stirring speed was checked using a revolution counter and also stop-watch for low speeds.

Inside the tanks clean copper coils where also mounted with their axis coincident with the axis of the vessels. Mean diameter of the coils were 16.00±0.2 cm (63 in) and height of each coil from the vessel bottom was 2.0±0.1 (0.8 in).

Tap water was fed to cold water reservoir. The level of the water in the reservoir was kept constant to prevent variation of the head to the feed pump. By manipulating the value on the exit side of the pump, water level in the tank and the cold water flowrate were adjusted. Also a continuous discharge was obtained by another pump at the exit of the tank.

Hot water was pumped from a constant temperature bath into the coil also by means of a rotary pump.

Directions of flow of the cold and hot water were opposite, i.e. counter-current. For all the runs reported a liquid depth of 17.0±0.1 cm (6.7 in) was used and the area of heating surface exposed the mixing liquid for each coil was 598.5 cm^2 (92.8 in^2). Cold and hot water flowrates were measured by collecting water in a graduated cylinder for periods of one or two minutes.

For two tanks in series, another dimensionally similar tank was connected to the previous single tank, the arrangement of the coil, stirrer and as well as water level in the tanks were kept same. As shown in Figure 4.2, outlet of the tank I was 50 cm higher from the inlet of the tank II to maintain the flow of cold water. Unfortunately, water level in the tanks changed with time. In order to prevent this situation, another pump was placed between two tanks. Again all connections were insulated carefully.

Figure 4.1 shows the thermocouple arrangements for the single tank. Seven thermocouples were used in this system. Three were installed into tank, hot water reservoir and cold water reservoir. And others were used to measure hot and cold water inlet and outlet temperatures. For two tanks in series twelve thermocouples were placed as shown in Figure 4.2. Four were installed into tank I and II, hot water and cold water reservoir. Others were used to measure hot and cold water inlet and outlet temperatures for tank I and tank II. All thermocouples were placed in small holes on the rubber connection pipes and sealed by liquid joint. Before putting thermocouples in their places, they were connected to the digital thermometer and controlled against one another in water at room temperature and at 60, 80°C and also checked with another digital thermometer.

No baffles were present in the vessel. However some baffling was obtained by the presence of the coil thermocouples and the stirrer.

All time measurements were taken with a stop-watch and at least three readings were taken for each measurement.

In this thesis study with the vessels having the configurations showing in Figure 4.3, the range of the parameters were as follows:

1. Reynolds number range, $1100 < N_{Re} < 14000$ (for coil side)
2. Ratio of the agitator diameter to tank diameter,

   D_A/D_T : 0.400
3. Ratio of agitator height to tank diameter,

   H_A/D_T : 0.300
4. Ratio of impeller blade width to impeller diameter,

   W_{ib}/D_A: 0.200
5. Ratio of coil diameter to tank diameter,

   D_c/D_T : 0.800
6. Ratio of coil length to tank diameter,

   L_c/D_T : 0.700
7. Ratio of coil tube diameter to coil diameter,

   D_H/D_c : 0.040
8. Ratio of the space between coils to coil tube diameter,

   S_c/D_H : 1.00
9. Ratio of coil height from vessel bottom to tank diameter,

   H_c/D_T : 0.10

4.C EXPERIMENTAL PROCEDURE

The experiments were performed in two sections as steady-state and unsteady-state cases for both two tanks in series and a single tank. In this investigation a Reynolds number range of 1100 to 14000 was used for flow in the coil.

4.C.1 Steady-State Experiments

In the first part this set of experiments, data were taken without changing cold water conditions and agitator speed. Only hot water flowrates were varied at different hot water temperatures and the procedure was as given below,

1. The mixer was set at desired speed and turned on.
2. Cold water was pumped into tank(s) at a certain flowrate. The water level in the tank(s) was kept constant and the same for both tanks.
3. Hot water at a given temperature was fed to coil(s) by a pump at a given flowrate.
4. Temperatures were recorded when steady-state conditions were reached.
5. After reaching steady-state and adjusting the hot water flowrate to new values, new steady-state temperatures were reached and recorded.
6. All these were repeated at different hot water temperatures.

For this part, the range of parameters are given in Table 4.1 and thirtyone runs were performed.

In the second part of the experiments, only agitator speed was changed for given constant hot water and cold water conditions. The complete procedure was,

1. The agitator was set at desired speed and turned on.
2. Tap water from the reservoir was pumped into tank(s) at a given flowrate.
3. Hot water at a given temperature was fed to coil(s) by a rotary pump at a given flowrate.
4. Sufficient time was allowed for a steady-state conditions to be achieved before recording the temperatures.
5. Changing only agitator speed (four times) this procedure was repeated.

The range of parameters for this part are given in Table 4.2 and eight runswere performed.

TABLE 4.1 - Range of Parameters for Single Tank and Two Tanks in Series (Hot stream flowrate is variable)

Parameters	Single Tank	Two Tanks in Series
Agitator speed (rpm)	200	200
Hot water inlet temperature (°C)	83.5-60.3	80.8-60.4
Cold water inlet temperature (°C)	17.5- 8.9	17.4-12.5
Hot water flowrate (ml/sec)	27.5- 5.6	16.6- 5.7
Cold water flowrate (ml/sec)	22.5-18.5	24.0-28.0

TABLE 4.2 - Range of Parameters for Single Tank and Two Tanks in Series (Agitator speed is variable)

Parameters	Single Tank	Two Tanks in Series
Agitator speed (rpm)	200-500	200-500
Hot water inlet temperature (°C)	75.6-75.0	74.5-70.3
Cold water inlet temperature (°C)	12.6-12.5	15.3-12.2
Hot water flowrate (ml/sec)	26.5-26.3	15.1-15.0
Cold water flowrate (ml/sec)	23.5-22.3	30.2-30.0

4.C.2 Unsteady-State Experiment

In this set of experiments, data were taken at given cold and hot water flowrates and agitator speed. Only the hot water inlet temperature was changed. Temperatures were recorded at every thirty seconds until steady-state was reached. The procedure given below was followed.

1. Agitator was set at the desired speed and turned on.
2. Top water at a given temperature and flowrate was pumped into tank(s).
3. Hot water at a given temperature was fed to coil(s) by pump at a given flowrate.
4. When steady-state was reached, temperatures were recorded. The hot water inlet temperature changed suddenly and the temperatures were recorded at every thirty seconds until new steady-state conditions were reached.

For this part the range of parameters are given in Table 4.3 and six runs were performed.

TABLE 4.3 - Range of Parameters for Unsteady-State Runs

Set	Hot Water Inlet Temperature (°C)	Cold Water Inlet Temperature (°C)	Cold Water Flowrate (ml/sec)	Hot Water Flowrate (ml/sec)
SINGLE TANK				
1	81.3-67.0	15.2	20.0	18.2
2	69.0-59.8	13.7	20.0	20.0
3	83.8-63.5	12.9	20.1	20.0
TWO TANK IN SERIES				
1	81.0-69.3	12.5	22.0	15.0
2	71.0-61.8	13.2	24.0	15.5
3	82.7-60.9	13.7	28.5	13.5

*Agitator speed was kept at 200 rpm for all sets.

V. RESULTS

Within the context of the work, overall heat transfer coefficient, external and internal film heat transfer coefficients were determined. First a graphical method known as the Modified Wilson plot [29] was used to evaluate the heat transfer coefficients and secondly on iterative computer program for each system, both single tank and two tanks in series was developed calculating heat transfer coefficients from the empirical equations and also temperatures. Complete sets of experimental data are presented in Appendix I.

5.A EVALUATION OF EXPERIMENTAL RESULTS

Both steady-state and unsteady-state results are analyzed in the following sections separately.

5.A.1 Steady-State Results

The results of the steady-state experiments were studied in two sections.

a) Determination of the overall heat transfer coefficient.

b) Graphical estimation of internal and external film heat transfer coefficients.

5.A.1.a Determination of the Overall Heat Transfer Coefficient

Overall heat transfer coefficients were calculated from the experimental data directly by using the fundamental equations given below:

$$U = \frac{Q}{A_o \Delta T_{\ell m}} \tag{5.1}$$

where, $\Delta T_{\ell m}$ is the logarithmic mean temperature difference, driving force between tank liquid and heating water. Temperature profiles are shown in Figures 5.1 and 5.2 for both single tank and two tanks in series.

A_o, heat transfer area of coil is the total wetted area, based on outside surface of the coil. The outside heat transfer area was calculated knowing the total wetted length and the outside diameter of the coil tube.

Q is the total heat transferred and was calculated on the basis of both the hot stream and the cold stream to check heat loss. Calculations were made using total heat based on hot stream.

5.A.1.b Graphical Estimation of External and Internal Film Heat Transfer Coefficient

Since only overall coefficients were measured directly, it was necessary to calculate internal and external coefficients from the data obtained. The results were interpreted by a graphical method similar to that proposed by Wilson [29]. This method is described in Section 2.D in detail. Figures for single tank are given through 5.3 to 5.6. for two tanks in series through 5.7 to 5.10.

As shown in Section 2.D for case I, (i.e. conditions of flow and temperature inside the coil not changing appreciably, only agitator speed changing). External and Internal heat transfer coefficients were determined by the use of Eq. 2.13, i.e.

$$\frac{1}{U} = \beta + \frac{1}{K\ N^{0.62}}$$

and Eq. 2.14, i.e.

$$\beta = \frac{1}{h_i}\ \frac{A_o}{A_i} + \frac{x}{k}\ \frac{A_o}{A_m} = \text{Constant}$$

Because of very thin wall of the coil tubing, A_i, A_o, and A_m, the outside, inside and average areas respectively, were taken as being equal to each other. By plotting $1/U$ versus $1/N^{0.62}$ a substantially straight line is obtained. To determine the value of the slope of the straight line, the method used is the least squares fit. Figure 5.3 shows the data for single tank, while Figure 5.7 represents the data for the two tanks in series. In this way from slope "1/K" the external film coefficient $HO = K\ N^{0.62}$ was determined as a function of agitator speed, and, from intercept "β" the internal film coefficient $HI = 1/(\beta - (x/k))$, was determined. Here x is thickness of the coil tubing and k, thermal conductivity of copper was taken as 385 $W/m^2 °C$ [6]. In Figure 5.3 from the intercept the internal film coefficient was calculated as 6711 $W/m^2 °C$, and from the slope the external film coefficient was calculated as a function of agitator speed. Results are tabulated for runs 1 to 4 in Table 5.3. Using Figure 5.7 the internal film coefficients

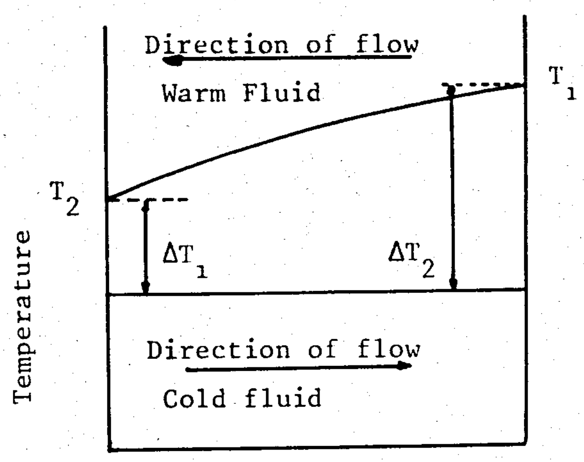


Figure 5-I. Temperature profile for single tank.

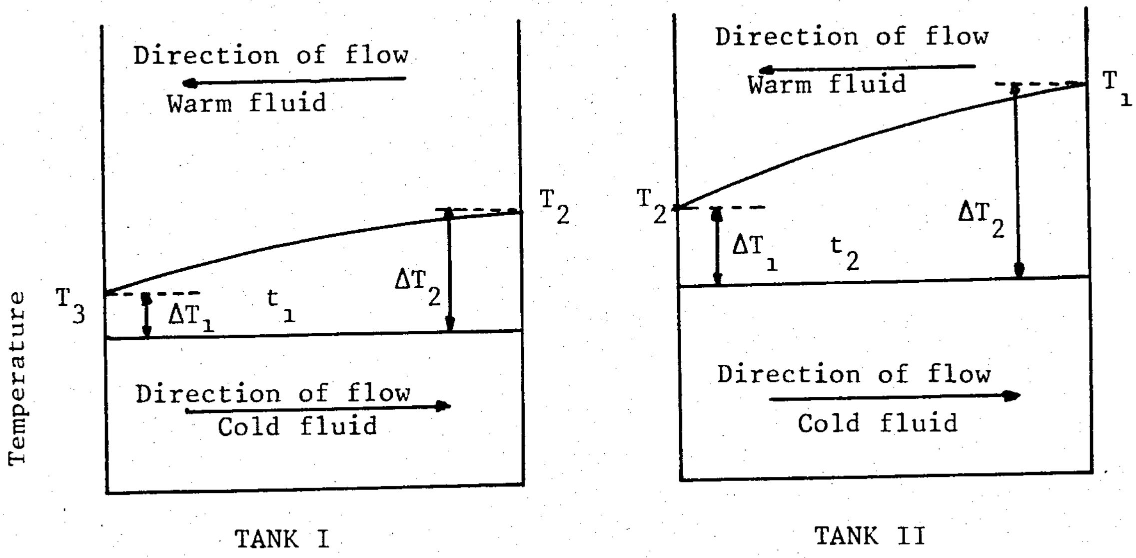


Figure 5-2. Temperature profile for two tanks in series.

for tank I 3225 $W/m^2°C$, for tank II 4269 $W/m^2°C$ were found. These values are almost half of those of a single tank. The reason is that hot water flowrate in two tanks in series system is half of that of single tank. Results representing heat transfer coefficients are tabulated in Table 5.5 from run 21 to 24.

As described in Section 2.D for Case II (i.e. conditions of flow, temperature outside the coil and agitator speed not changing appreciably, and only water flowrate inside the coil changing) external and internal heat transfer coefficients were determined by using Eq. 2.15. i.e.

$$\frac{1}{U} = \gamma + \frac{1}{K'V^{0.8}}$$

and Eq. 2.16, i.e.

$$\gamma = \frac{1}{HO}\frac{A_i}{A_o} + \frac{x}{k}\frac{A_i}{A_m} \quad \text{(constant)}$$

by thin wall assumption (i.e. $A_i = A_o = A_m$). A plot of 1/U versus $1/V^{0.8}$ yields a straight line with an intercept of at the ordinate γ and a slope of 1/K'. Again the least square fit was used to determine the value of the slope of the straight line. In this way from the slope, the internal film coefficient $HI = K'V^{0.8}$ was calculated as function of hot stream velocity. From the intercept, the external film coefficient, $HO = 1/(\gamma - (x/k))$ was determined as a constant. For each set at least five runs were performed. For the single tank system, the hot water flowrate inside the coil changed from 27.5 ml/sec to 5.7 ml/sec, while the hot water inlet temperature was varied as 81.4, 73.0 and 61.8°C respectively for each set. For two tanks in series, the hot water flowrate was varied from 16.6 ml/sec to 5.7 ml/sec and hot water inlet temperature changed as 80.5, 71.5 and 60.9°C for each set.

In single tank experiments represented in Figure 5.4, (runs 5 to 10) from the intercept, the external film coefficient was found as 4255 $W/m^2 °C$ (749 Btu/hr.sq.ft) at N_{Re}= 29.000 (average in agitated side). From the slope the internal film coefficient was calculated to be 2928 $W/m^2 °C$ (516 Btu/hr.sq ft.°F - at a water velocity of one foot per second), at N_{Re} = 4112 (inside the coil). As, for Figure 5.5 (runs 11 to 15) at N_{Re} = 26.000 (agitated side) the external film heat transfer coefficient is 4219 $W/m^2 °C$ (743 Btu/hr.sq ft.°F), and the internal film heat transfer coefficient, at N_{Re} = 3761 (inside the coil) is 2916 $W/m^2 °C$ (513 Btu/hr.sq ft.°F) at a water velocity of one foot per second. For Figure 5.6 (runs 16 to 20) the external film coefficient, at N_{Re} = 24.000 (agitated side) is 4016 $W/m^2 °C$ (707 Btu/hr.sq ft.°F) and the internal film coefficient. at N_{Re} = 3165 (inside the coil), is 2610 $W/m^2 °C$ (460 Btu/hr.sq ft.°F - at a water velocity of one foot per second). All results for the single tank are given in Table 5.4.

For two tanks in series (Figure 5.8 - runs 25 to 29) for tank I, at N_{Re} = 27.000 (agitated side) external film heat transfer coefficient is 4266 $W/m^2 °C$ (751 Btu/hr.sq ft.°F) and internal film coefficient at N_{Re} = 2736 (inside the coil) is, 2720 $W/m^2 °C$ (479 Btu/hr.sq ft.°F) at a water velocity one foot per second. For tank II, at N_{Re} = 38.100 (agitated side) external film heat transfer coefficient is 4830 $W/m^2 °C$ (850 Btu/hr.sq ft.°F) and internal film coefficient at N_{Re} = 4353 (inside the coil), is 2760 $W/m^2 °C$ (486 Btu/hr.sq ft.°F) at water velocity one foot per second. All results for two tanks in series are given in Table 5.6 and also are represented on Figures 5.9 and 5.10. The speed of the agitator remained constant at 200 rpm for both single tank and and two tanks in series.

Also to observe the effect of agitator speed on external film heat transfer coefficient. Logarithmic plot of agitator speed vs external film coefficient was plotted in Figure 5.11 for two tanks in series. Figure 5.12 for single tank. First this data were fitted a straight line, slopes were found 0.60 for single tank, for two tanks in series, tank I and tank II 0.59, 0.62 respectively. But when these data were fitted a second order polinomial, (i.e. $\ln HO = A + B\ln N + C(\ln N)^2$) coefficient of the second order variable was found unexpectedly 0.33 for single tank, for two tanks in series -0.26, -0.31 for tank I and tank II respectively. So, as a result it is impossible to observe asymptotic values for agitator speed from these data.

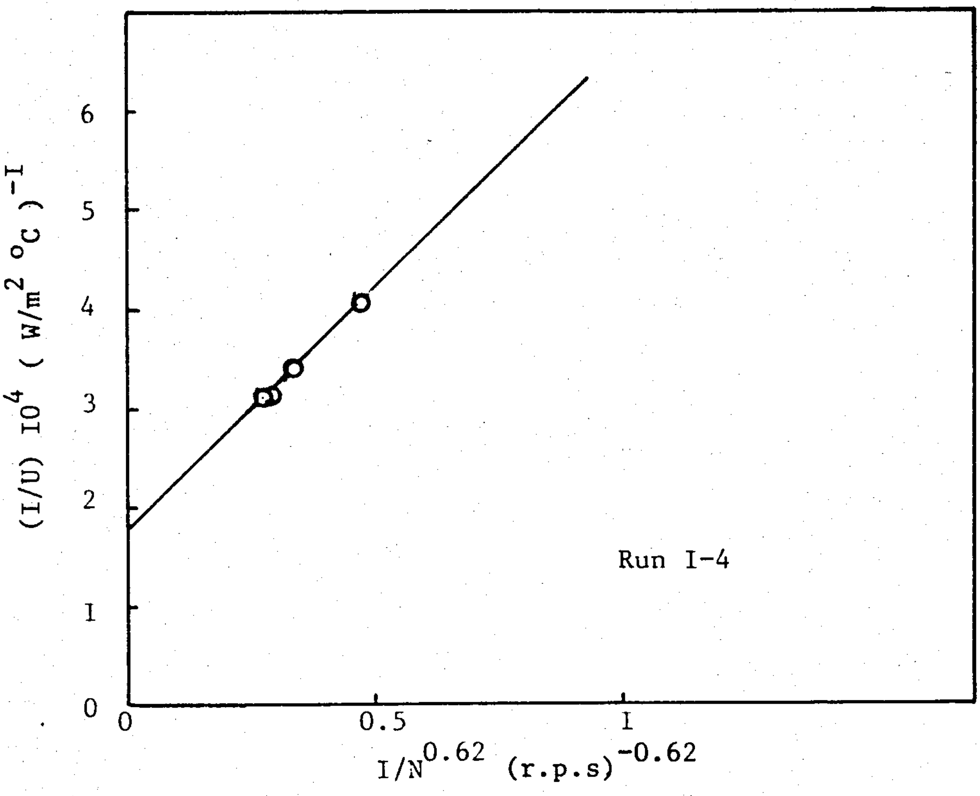


Figure 5-3. Modified Wilson plot for single tank.

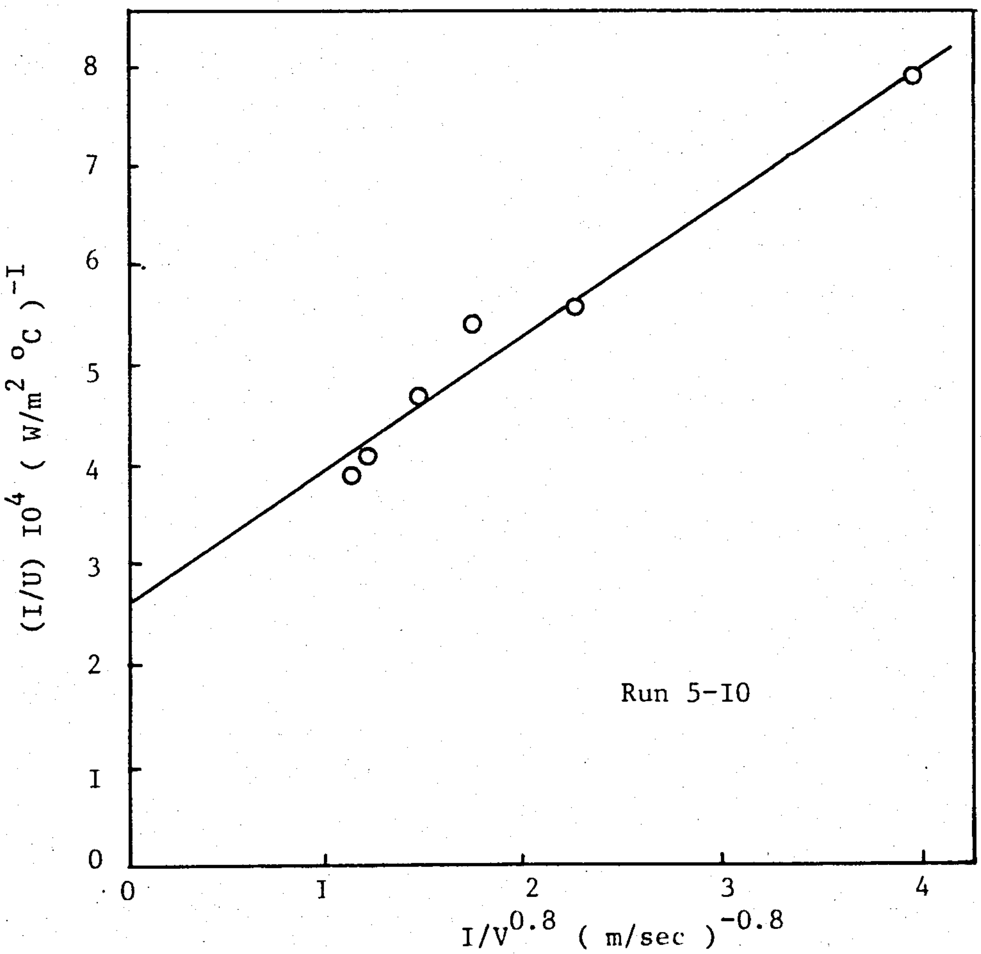


Figure 5-4.Modified Wilson plot for single tank.

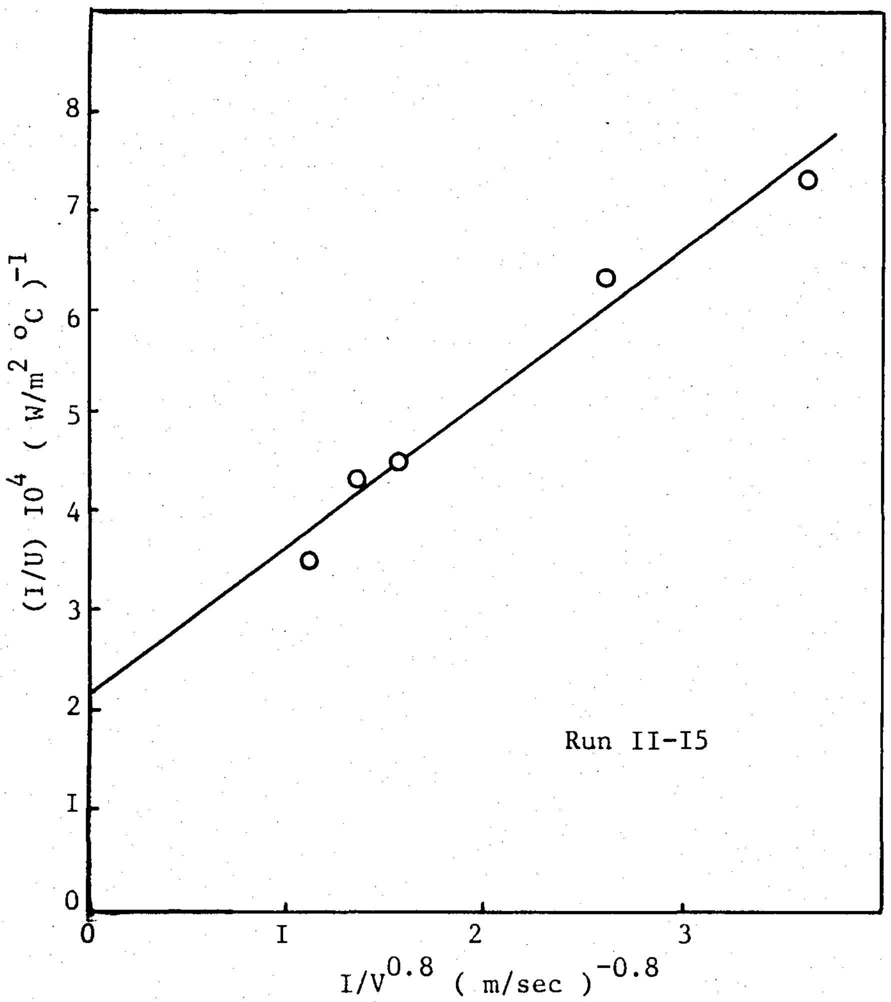


Figure 5-5. Modified Wilson plot for single tank.

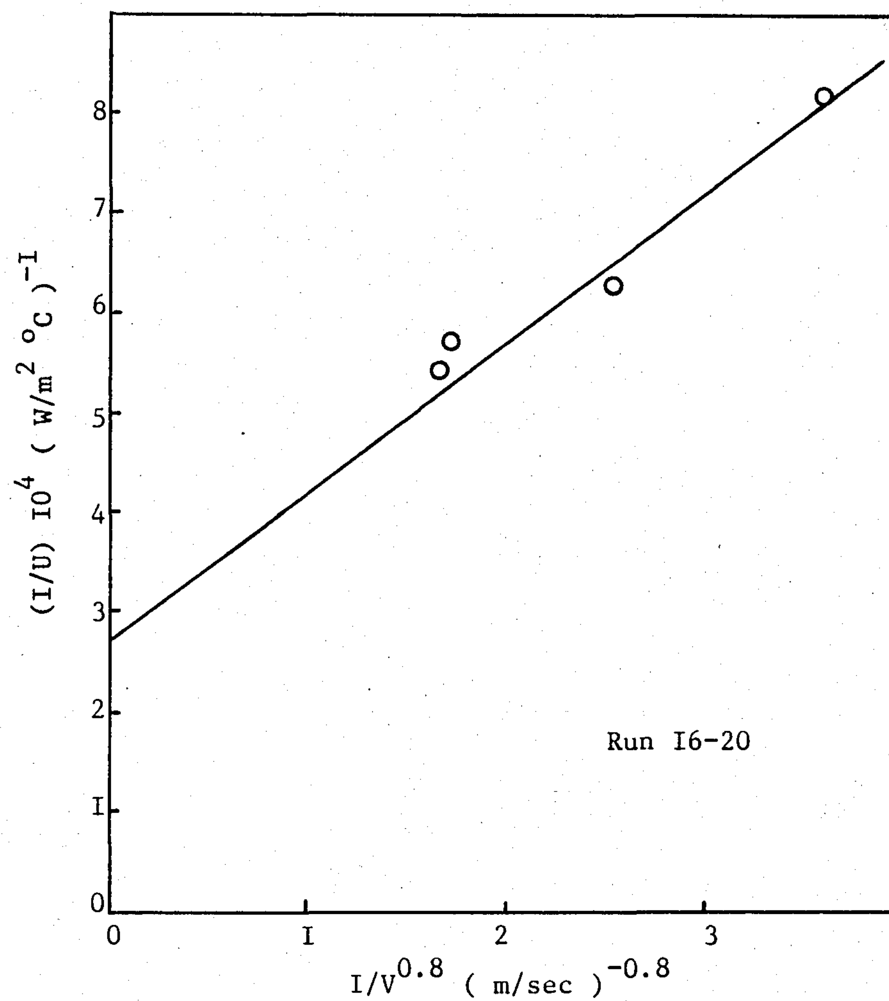


Figure 5-6. Modified Wilson plot for single tank.

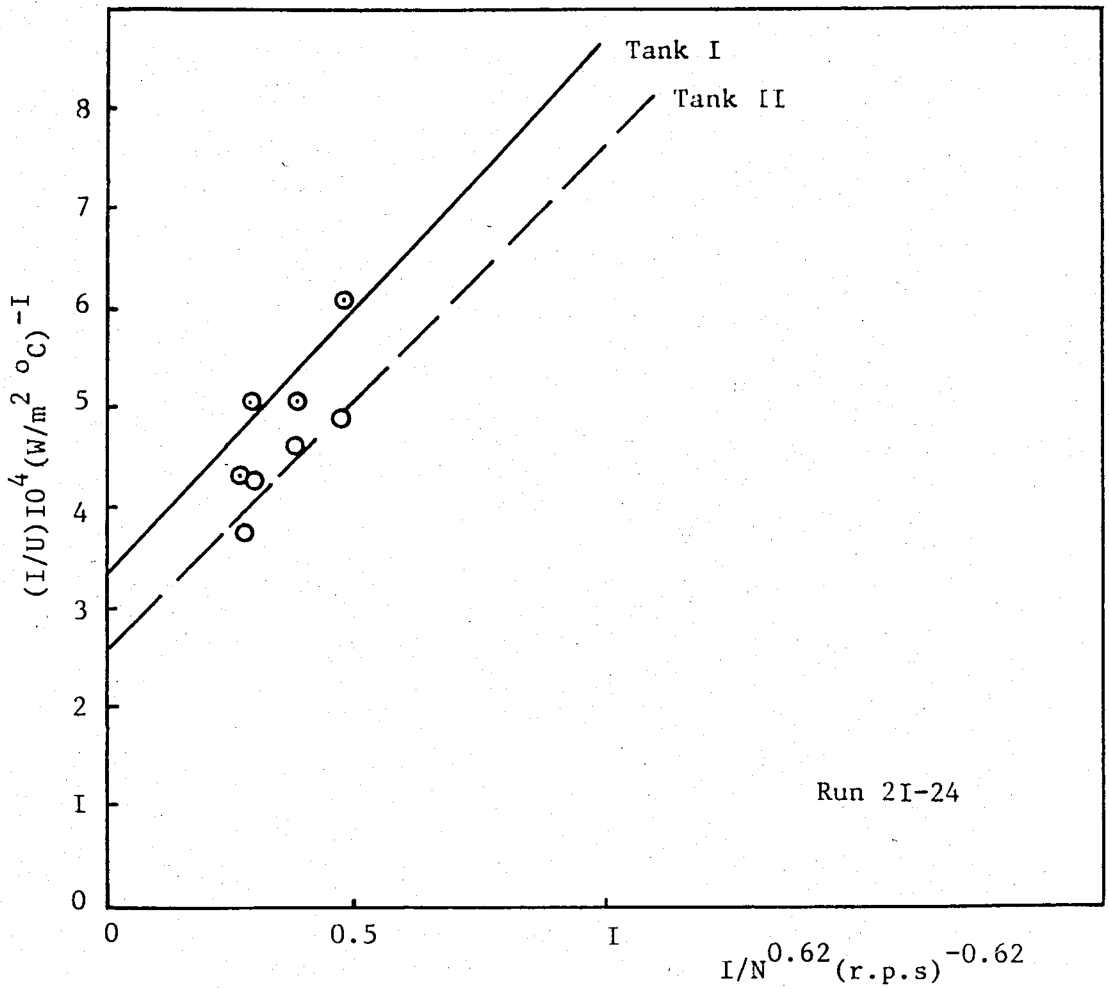


Figure 5-7.Modified Wilson plot for two tanks in series.

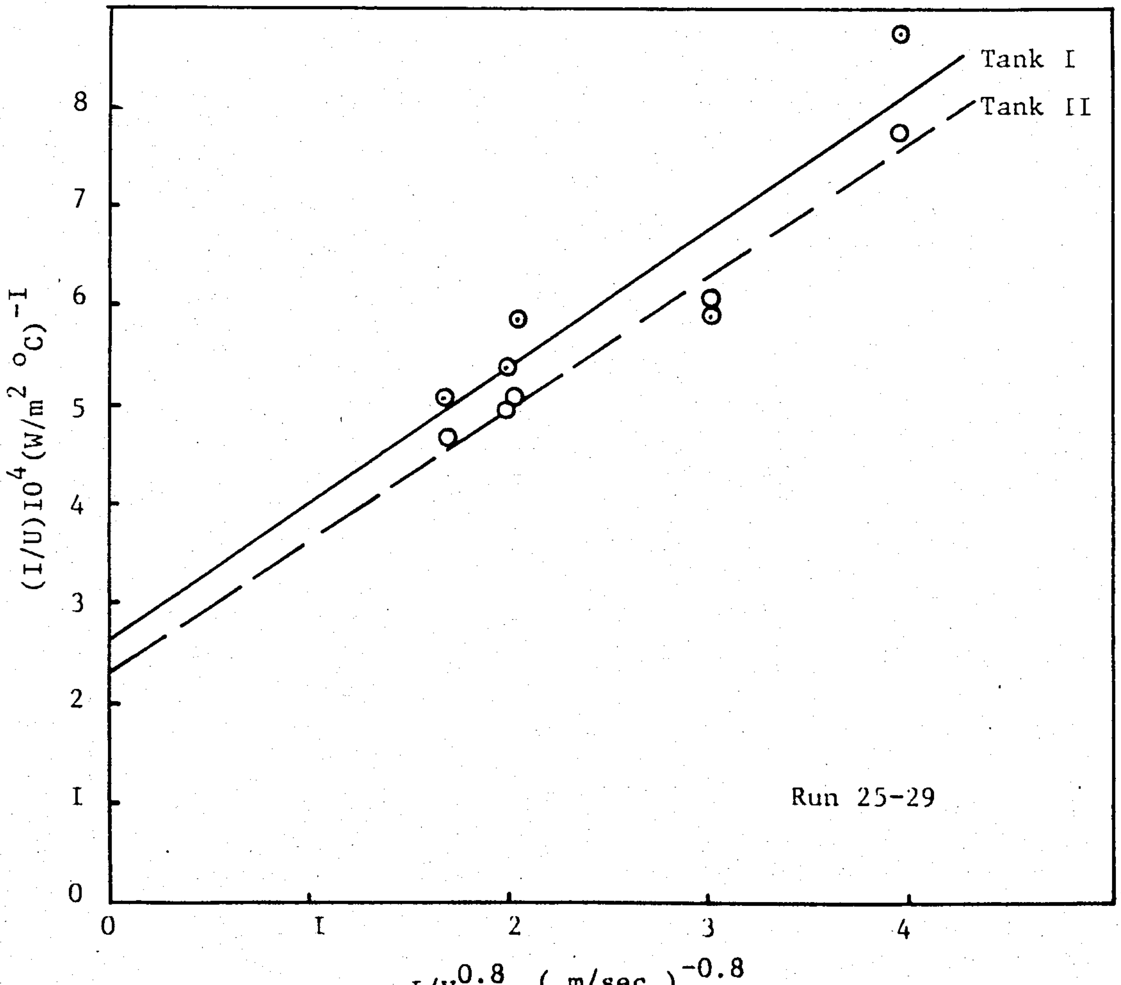


Figure 5-8.Modified Wilson plot for two tanks in series.

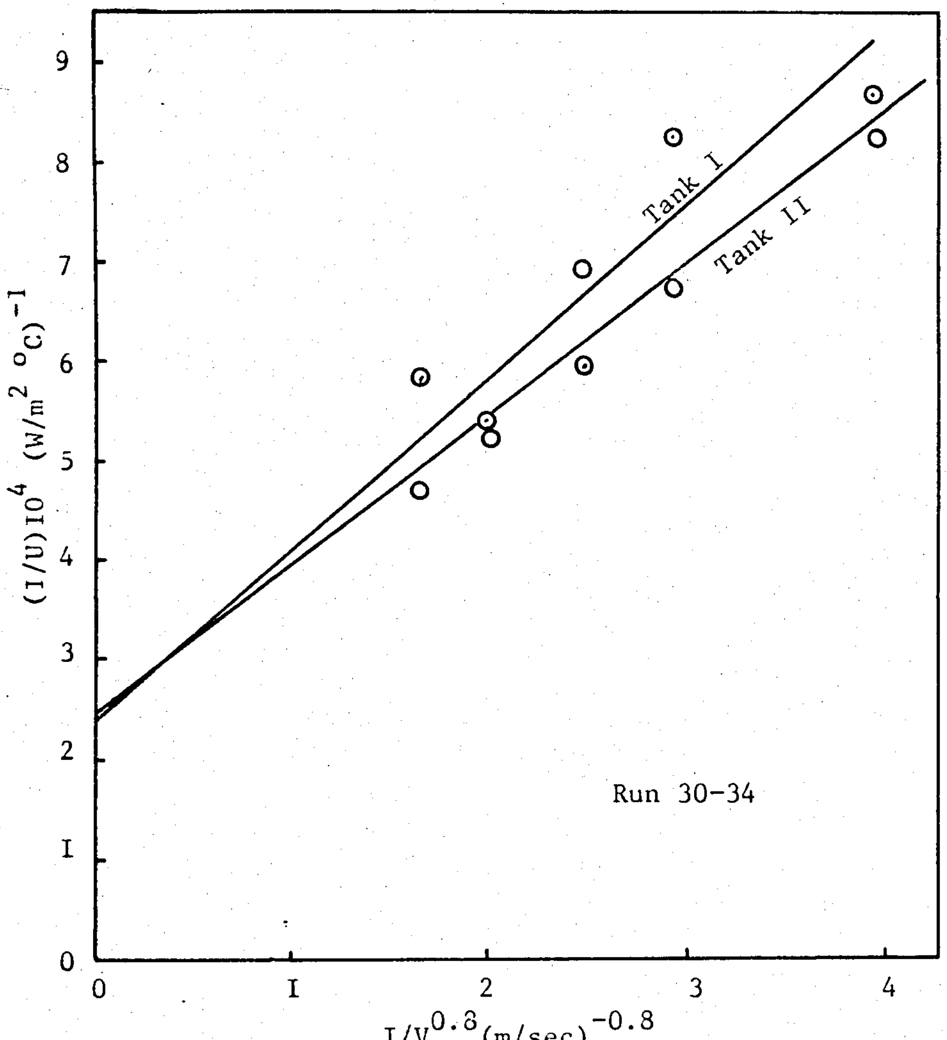


Figure 5-9.Modified Wilson plot for two tanks in series.

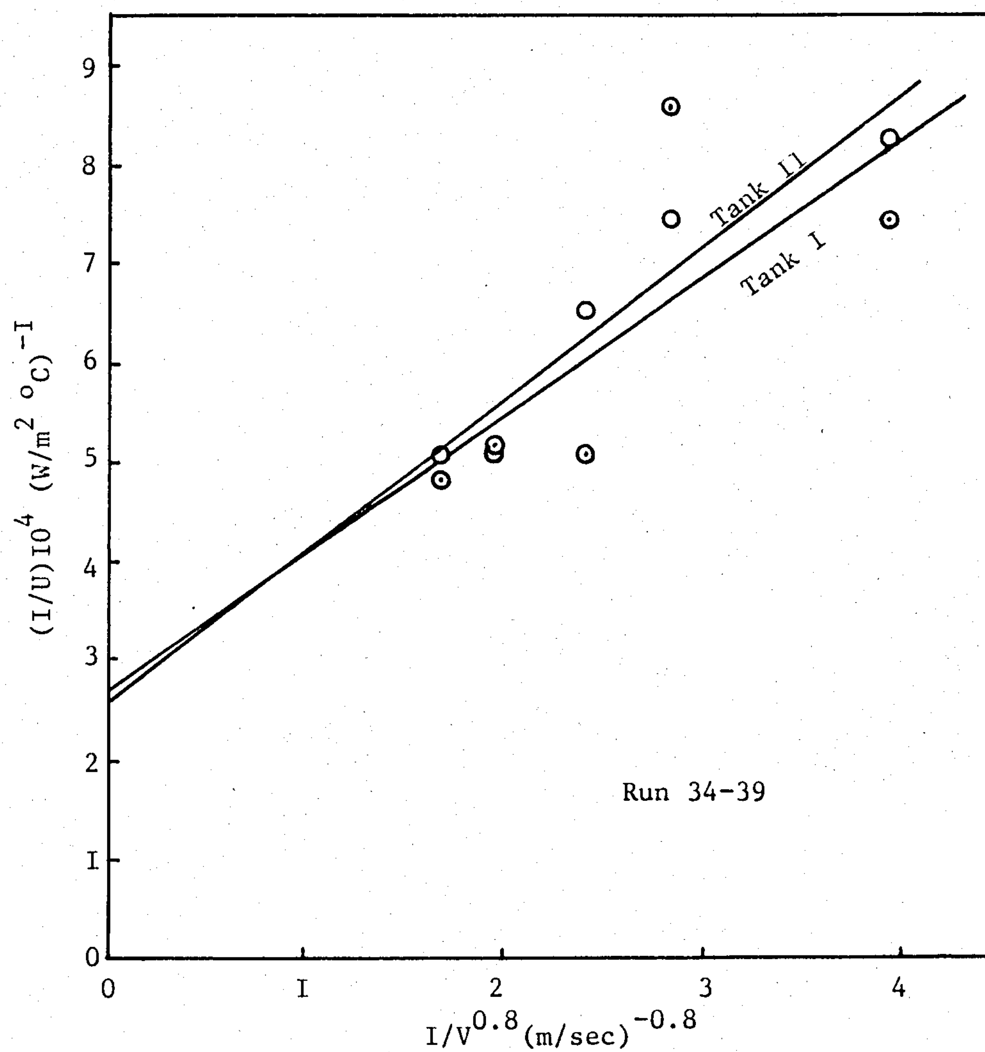


Figure 5-I0.Modified Wilson plot for two tank in series.

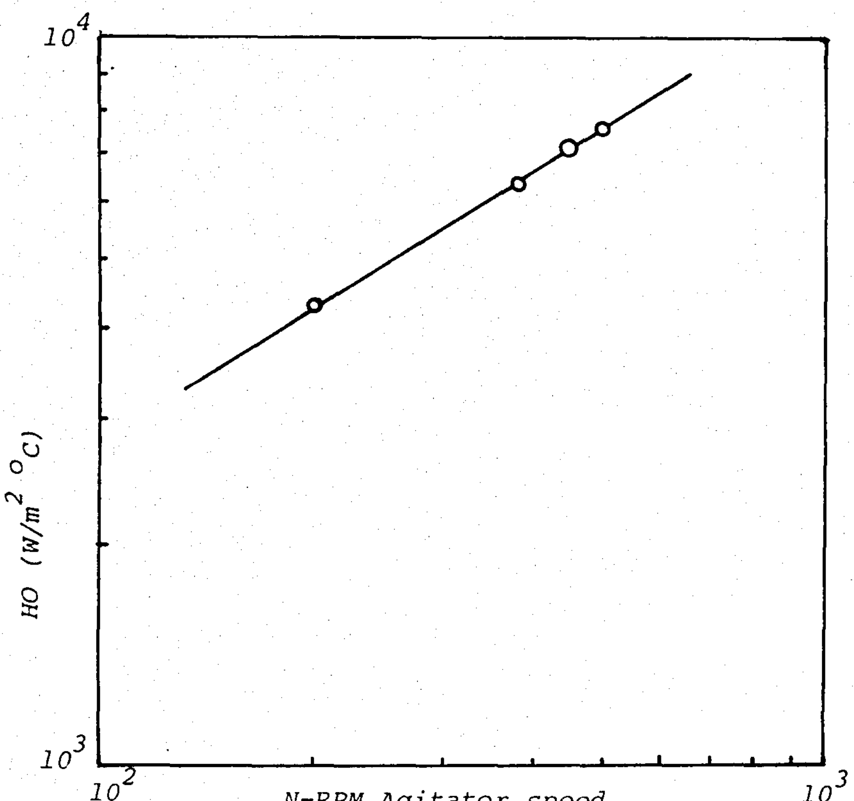


Figure 5-12.Relationship between film heat transfer coefficient and agitator speed.

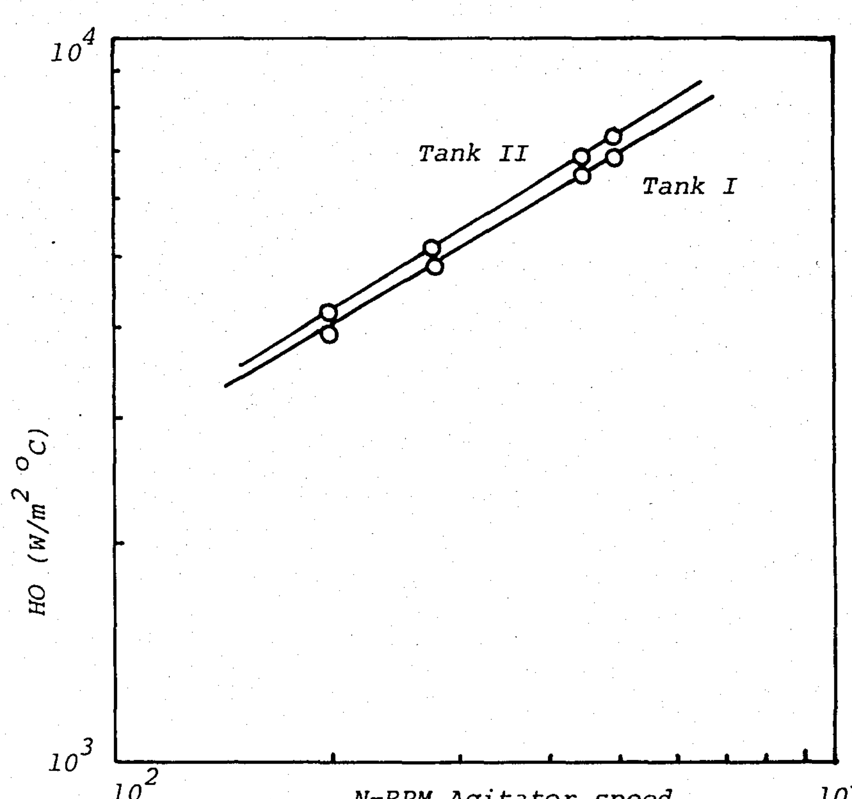


Figure 5-11.Relationship between film heat transfer coefficient and agitator speed.

TABLE 5.1 - Sample Temperature - Time Data - Observed

Set No: 1 (Two tanks in series)
N : 200 rpm
W : 15.0 ml/sec
M : 22.0 ml/sec
TCO(1): 12.5°C
TH1(1): 81.0°C

TC1S	TC2S	TH2S	TH3S
26.0	45.9	49.6	29.8

TCO(2): 12.5°C
TH1(2): 69.3°C

Time (sec)	TC1 °C	TC2 °C	TH2 °C	TH3 °C	ALPHA*	BETA**
30	25.8	45.1	47.8	29.3	0.159	0.112
60	25.6	44.5	47.1	29.0	0.158	0.105
90	25.4	43.9	46.8	28.8	0.159	0.114
120	25.3	43.6	46.6	28.6	0.155	0.116
150	25.2	43.1	46.1	28.5	0.158	0.114
180	25.0	42.7	45.8	28.3	0.159	0.116
210	24.9	42.5	45.7	28.1	0.154	0.119
240	24.8	42.2	45.5	28.0	0.155	0.121
270	24.7	42.0	45.3	27.9	0.155	0.120
300	24.6	41.8	45.3	27.7	0.150	0.127
330	24.5	41.6	45.1	27.6	0.151	0.126
360	24.4	41.5	45.0	27.5	0.151	0.125
390	24.3	41.3	45.0	27.4	0.150	0.132
420	24.2	41.1	44.8	27.3	0.151	0.137
450	24.0	41.1	44.7	27.3	0.159	0.127
480	23.9	41.0	44.6	27.2	0.159	0.127
510	23.9	40.9	44.6	27.2	0.159	0.130
540	23.8	40.9	44.5	27.1	0.159	0.126
570	23.7	40.8	44.4	27.1	0.164	0.126
600	23.7	40.7	44.3	27.1	0.165	0.125
630	23.7	40.7	44.3	27.1	0.165	0.125
660	23.7	40.7	44.3	27.1	0.165	0.125

* $\frac{TH3 - TC1}{TH2 - TC1}$

** $\frac{TH2 - TC2}{TH1(2) - TC2}$

TABLE 5.2 - Sample Temperature - Time Data - Calculated

Set No: 1
N : 200 rpm
W : 15.0 ml/sec
M : 22.0 ml/sec
TCO(1): 12.5°C
TH1(1): 81.0°C

TC1S	TC2S	TH2S	TH3S
26.23	46.64	50.84	30.55

TCO(2): 12.5°C
TH2(2): 69.3°C

Time (sec)	TC1 °C	TC2 °C	TH2 °C	TH3 °C
30	26.09	45.63	48.64	30.04
60	25.92	44.83	47.94	29.78
90	25.74	44.19	47.38	29.53
120	25.56	43.66	46.92	29.30
150	25.38	43.23	46.55	29.09
180	25.22	42.87	46.24	28.90
210	25.07	42.58	45.98	28.73
240	24.94	42.32	45.76	28.58
270	24.81	42.11	45.57	28.45
300	24.71	41.93	45.41	28.34
330	24.61	41.78	45.28	28.23
360	24.53	41.65	45.17	28.14
390	24.45	41.53	45.07	28.07
420	24.39	41.44	44.98	28.00
450	24.33	41.35	44.91	27.94
480	24.28	41.28	44.85	27.89
510	24.24	41.22	44.79	27.84
540	24.20	41.17	44.74	27.80
570	24.17	41.12	44.70	27.77
600	24.14	41.08	44.67	27.74
630	24.12	41.04	44.64	27.71
660	24.10	41.01	44.61	27.69
690	24.08	40.99	44.59	27.67
720	24.06	40.96	44.57	27.66
750	24.05	40.94	44.55	27.64
780	24.04	40.93	44.54	27.63
810	24.02	40.91	44.52	27.62
840	24.02	40.90	44.51	27.61
870	24.01	40.89	44.50	27.60
900	24.00	40.88	44.49	27.59
930	23.99	40.87	44.49	27.59
960	23.99	40.86	44.48	27.58
990	23.98	40.86	44.48	27.58

./...

TABLE 5.2 - Continued..

Time (sec)	TC1 °C	TC2 °C	TH2 °C	TH3 °C
1020	23.98	40.85	44.47	27.57
1050	23.98	40.85	44.47	27.57
1080	23.97	40.84	44.46	27.56
1110	23.97	40.84	44.46	27.56
1140	23.97	40.84	44.46	27.56
1170	23.97	40.83	44.45	27.56
1200	23.97	40.83	44.45	27.56
1230	23.96	40.83	44.45	27.55
1260	23.96	40.83	44.45	27.55
1290	23.96	40.83	44.45	27.55
1320	23.96	40.82	44.45	27.55
1350	23.96	40.82	44.45	27.55
1380	23.96	40.82	44.44	27.55
1410	23.96	40.82	44.44	27.55

TABLE 5.3 - Comparison of Experimental Results and Computed Results (SINGLE TANK)
- Agitator speed was changed -

Run	Agitated Speed (rpm)	Experimental Results			Computed Results		
		HI ($W/m^2 °C$)	HO ($W/m^2 °C$)	U ($W/m^2 °C$)	HI ($W/m^2 °C$)	HO ($W/m^2 °C$)	U ($W/m^2 °C$)
1	200	6711	4334	2465	6788	4692	2588
2	380	6711	6365	3011	6738	6983	3148
3	450	6711	7023	3151	6676	7741	3278
4	500	6711	7544	3252	6674	8225	3362

* Hot water flowrate (ml/sec) : 26.5

* Hot water inlet temperature (°C) : 75.5

* Cold water inlet temperature (°C): 12.6

* Cold water flowrate (ml/sec) : 22.7

TABLE 5.4 - Comparison of Experimental Results and Computed Results (SINGLE TANK)
- Hot stream flow rate was changed -

Run	Hot Stream Flowrate (ml/sec)	Experimental Results			Computed Results		
		HI ($W/m^2{}^\circ C$)	HO ($W/m^2{}^\circ C$)	U ($W/m^2{}^\circ C$)	HI ($W/m^2{}^\circ C$)	HO ($W/m^2{}^\circ C$)	U ($W/m^2{}^\circ C$)
5	27.5	6663	4255	2432	7395	4892	2735
6	25.0	6219	4255	2370	6700	4801	2607
7	19.8	5077	4255	2183	5397	4662	2349
8	16.0	4289	4255	2020	4530	4616	2158
9	11.2	3302	4255	1773	3284	4452	1801
10	5.6	1894	4255	1267	1763	4164	1200

*Agitator speed (rpm) : 200.0

*Hot water inlet temperature (°C) : 81.4

*Cold water inlet temperature (°C): 10.5

*Cold water flowrate (ml/sec) : 19.5

TABLE 5.4 - Continued..

Run	Hot Stream Flowrate (ml/sec)	Experimental Results			Computed Results		
		HI ($W/m^2 °C$)	HO ($W/m^2 °C$)	U ($W/m^2 °C$)	HI ($W/m^2 °C$)	HO ($W/m^2 °C$)	U ($W/m^2 °C$)
11	27.5	6663	4219	2420	6988	4738	2630
12	21.5	5487	4219	2246	5693	4726	2420
13	18.5	4815	4219	2124	4932	4613	2244
14	9.6	2870	4219	1635	2744	4303	1605
15	6.3	2062	4219	1337	1909	4225	1274

*Agitator Speed (rpm) : 200.0

*Hot water inlet temperature (°C) : 73.0

*Cold water inlet temperature (°C): 15.9

*Cold water flowrate (ml/sec) : 20.3

TABLE 5.4 - Continued..

Run	Hot Stream Flowrate (ml/sec)	Experimental Results			Computed Results		
		HI ($W/m^2 °C$)	HO ($W/m^2 °C$)	U ($W/m^2 °C$)	HI ($W/m^2 °C$)	HO ($W/m^2 °C$)	U ($W/m^2 °C$)
16	27.1	5880	4016	2247	6379	4490	2464
17	19.0	4003	4016	1905	4658	4372	2130
18	16.1	3063	4016	1662	4063	4355	1993
19	10.0	2637	4016	1529	2613	4129	1536
20	6.4	1851	4016	1226	1774	4006	1192

*Agitated Speed (rpm) : 200.0

*Hot water inlet temperature (°C) : 61.8

*Cold water inlet temperature (°C): 10.5

*Cold water flowrate (ml/sec) : 19.7

TABLE 5.5 - Comparison of Experimental Results and Results from the Computer (TWO TANKS IN SERIES)
- Agitated speed was changed -

EXPERIMENTAL RESULTS							
		TANK I			TANK II		
Run	Agitator Speed (rpm)	HI_1 ($W/m^2°C$)	HO_1 ($W/m^2°C$)	U_1 ($W/m^2°C$)	HI_2 ($W/m^2°C$)	HO_2 ($W/m^2°C$)	U_2 ($W/m^2°C$)
21	200	3225	3962	1699	4269	4194	2005
22	280	3225	4901	1851	4269	5188	2208
23	450	3225	6421	2033	4269	6799	2455
24	500	3225	6897	2079	4269	7302	2517
COMPUTED RESULTS							
21	200	3246	3960	1705	4202	4247	2002
22	280	3250	4890	1858	4225	5289	2213
23	450	3226	6540	2045	4127	7098	2443
24	500	3243	7059	2100	4125	7646	2505

*Hot stream flowrate (ml/sec) : 15.0
*Cold stream flowrate (ml/sec) : 30.0
*Cold water inlet temperature (ml/sec) : 13.4
*Hot water inlet temperature (ml/sec) : 72.3

TABLE 5.6 - Comparison of Experimental Results and Computed Results (TWO TANKS IN SERIES)
- Hot stream flowrate was changed -

EXPERIMENTAL RESULTS							
		TANK I			TANK II		
Run	Hot Stream Flowrate (ml/sec)	HI_1 ($W/m^2{}^\circ C$)	HO_1 ($W/m^2{}^\circ C$)	U_1 ($W/m^2{}^\circ C$)	HI_2 ($W/m^2{}^\circ C$)	HO_2 ($W/m^2{}^\circ C$)	U_2 ($W/m^2{}^\circ C$)
25	16.6	4257	4266	2019	4536	4830	2206
26	13.5	3605	4266	1859	3826	4830	2024
27	13.1	3464	4266	1821	3713	4830	1991
28	8.0	2332	4266	1450	2500	4830	1580
29	5.7	1794	4266	1222	1922	4830	1328
COMPUTED RESULTS							
25	16.6	3940	4265	1945	4813	4853	2274
26	13.5	3207	4167	1731	3999	4742	2054
27	13.1	3123	4160	1705	3908	4737	2028
28	8.0	1933	3983	1259	2482	4455	1530
29	5.7	1415	3910	1011	1835	4303	1245

*Agitator speed (rpm): 200.0
*Cold water inlet temperature (°C): 17.5
*Hot water inlet temperature (°C): 80.5
*Cold water flowrate (ml/sec) : 24.0

TABLE 5.6 - Continued...

EXPERIMENTAL RESULTS							
		TANK I			TANK II		
Run	Hot Water Flowrate (ml/sec)	HI_1 ($W/m^2 °C$)	HO_1 ($W/m^2 °C$)	U_1 ($W/m^2 °C$)	HI_2 ($W/m^2 °C$)	HO_2 ($W/m^2 °C$)	U_2 ($W/m^2 °C$)
30	16.2	3444	4386	1837	3992	4587	2022
31	13.4	2858	4386	1656	3313	4587	1832
32	10.2	2305	4386	1454	2672	4587	1617
33	8.2	1951	4386	1305	2261	4587	1457
34	5.7	1451	4386	1060	1682	4587	1192
COMPUTED RESULTS							
30	16.2	3605	4099	1827	4381	4589	2118
31	13.4	3009	4030	1649	3732	4518	1941
32	10.2	2314	3945	1405	2895	4374	1667
33	8.2	1890	3894	1231	2383	4281	1473
34	5.7	1364	3839	981	1729	4151	1183

*Agitator speed (rpm) : 200.0

*Hot water inlet temperature (°C): 71.5

*Cold water inlet temperature(°C): 15.9

*Cold water flowrate (ml/sec) : 28.0

TABLE 5.6 - Continued..

Run	Hot water Flowrate (ml/sec)	TANK I HI_1 ($W/m^2°C$)	TANK I HO_1 ($W/m^2°C$)	TANK I U_1 ($W/m^2°C$)	TANK II HI_2 ($W/m^2°C$)	TANK II HO_2 ($W/m^2°C$)	TANK II U_2 ($W/m^2°C$)
EXPERIMENTAL RESULTS							
35	16.5	4226	4132	1981	3865	4329	2068
36	13.5	3644	4132	1843	3313	4329	1843
37	10.4	2951	4132	1647	2683	4329	1561
38	8.6	2506	4132	1497	2278	4329	1369
39	5.7	1802	4132	1215	1648	4329	1041
COMPUTED RESULTS							
35	16.5	3469	3968	1766	4137	4394	2020
36	13.5	2884	3920	1593	3487	4333	1840
37	10.4	2256	3849	1372	2755	4222	1598
38	8.6	1892	3805	1223	2322	4145	1433
39	5.7	1312	3748	949	1616	4014	1118

*Agitator speed (rpm) : 200.0

*Hot water inlet temperature (°C) : 60.9

*Cold water inlet temperature (°C): 12.8

*Cold water flowrate (ml/sec): 20.0

*Average values.

5.A.2 Unsteady State Results

From the transient data obtained, the change in temperature with time was plotted in Figure 5.13 and in Appendix I, in Figures A.I.1 through A.I.5. And for single tank time versus Alpha = $\frac{TH2-TC1}{TH1-TC1}$ and for two tanks in series time versus Alpha = $\frac{TH3-TC2}{TH2-TC2}$ as well as time versus Beta = $\frac{TH2-TC2}{TH1-TC2}$ were plotted to check whether, the overall coefficient remains constant. At the same time $Alpha_1$ is given by $Alpha_1 = \exp[-U A/WC_h\rho_h]$ and Alpha and Beta are equal to $Alpha = \exp[-U_1A/WC_h\rho_h]$, $Beta = \exp[-U_2A/WC_h\rho_h]$. For example single tank set 2 average $Alpha_1$ was found to be 0.198 and is shown in Figure A.I.2 and in Table A.I.6 (Appendix I). Two tanks in series for set 1 Alpha = 0.157 and Beta = 0.122 values were calculated and also are tabulated in Table 5.1 and shown on Figure 5.13.

Time constants were determined for both single tank and two tanks in series. The value of tank temperature (TC1, TC2) reaches 63.2 percent of its ultimate value when the time elapsed is equal to one time constant [32]. For example considering two tanks in series and experiment set 1

for tank I

TC_0 = 26.0°C (value of tank temperature at the beginning)

TC_∞ = 23.7°C (ultimate value of the tank temperature)

$TC1_{\tau_1}$ = 24.5°C (value of tank temperature after one time constant elapsed)

from Figure 5.13 time constant was found to be τ_1 = 330 sec.

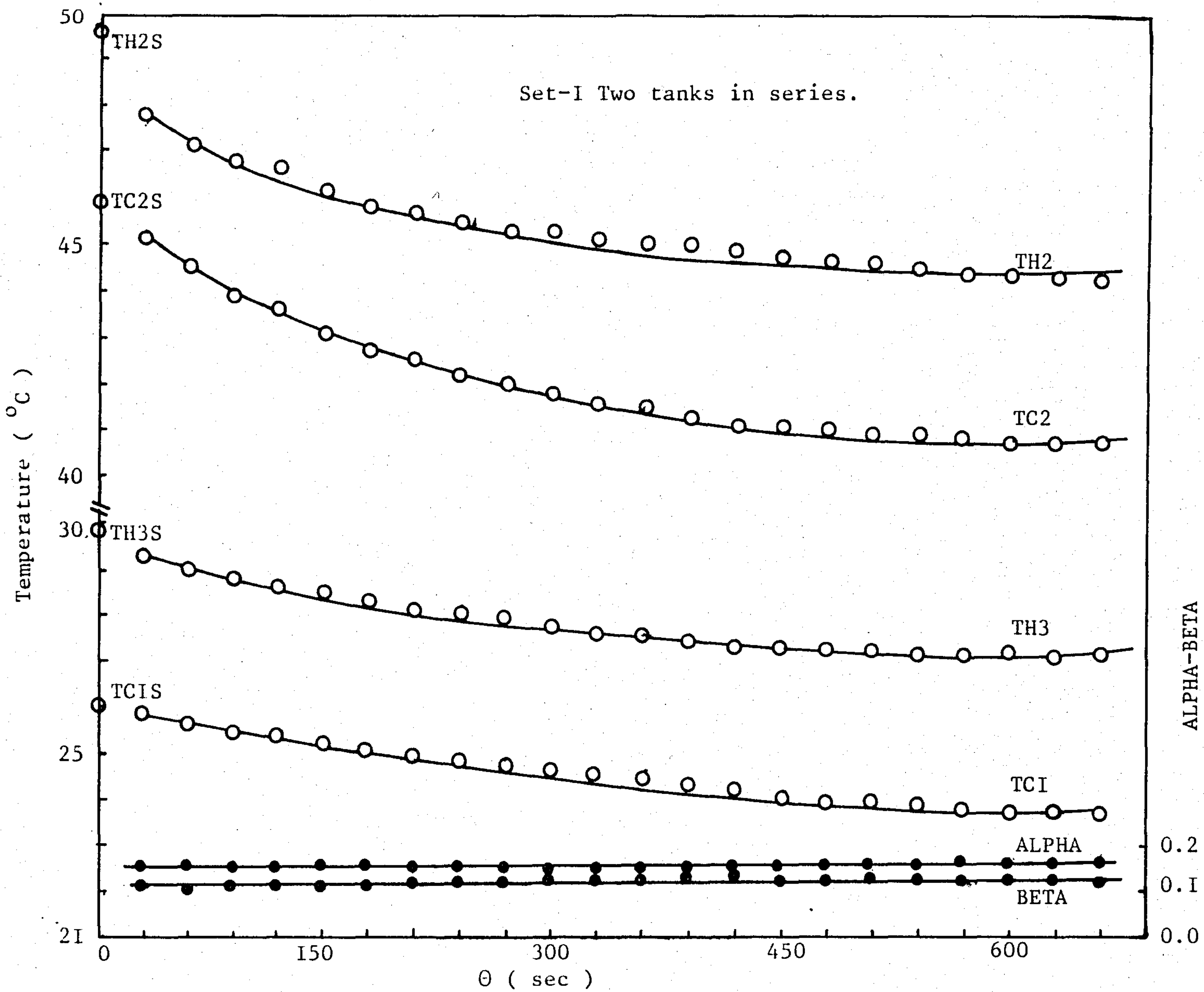


Figure 5-I3. Temperature change with time for unsteady-state heat transfer.

For tank II

$TC2_o = 45.9°C$

$TC2_\infty = 40.7°C$

and $TC2_{\tau_2} = 42.6°C$

again from Figure 5.13 time constant was found as $\tau_2 = 195$ sec.

From computed temperatures for the same set;

Tank I

$TC1_o = 26.23°C$

$TC1_\infty = 23.96°C$

$TC1_{\tau_1} = 24.75°C$

and $\tau_1 = 288$ sec

Tank II

$TC2_o = 46.64°C$

$TC2_\infty = 40.82°C$

$TC2_{\tau_2} = 42.96°C$

and $\tau_2 = 175$ sec

Tabulated results are presented in Tables 5.7 and 5.8. Other tables and graphs for unsteady-state sets are given in Appendix I.

TABLE 5.7 - Time Constant - Single Tank

Set No.	Observed				Computed			
	TCl_o °C	TCl_∞ °C	TCl_τ °C	τ (sec)	TCl_o °C	TCl_∞ °C	TCl_τ °C	τ (sec)
1	43.4	36.9	39.3	99	43.37	37.09	39.40	116
2	38.7	33.8	35.6	110	38.31	34.16	35.70	113
3	44.7	35.6	38.9	108	44.86	35.62	39.02	112

TCl_o = Value of tank temperature at beginning

TCl_∞ = Ultimate value of tank temperature

TCl_τ = Value of tank temperature after one time constant elapsed

τ = Time constant

TABLE 5.8 - Time Constants - Two Tank in Series

OBSERVED								
	TANK I				TANK II			
Set No.	$TC1_0$ °C	$TC1_\infty$ °C	$TC1_\tau$ °C	τ_1 sec	$TC2_0$ °C	$TC2_\infty$ °C	$TC2_\tau$ °C	τ_2 sec
1	26.0	23.7	24.5	330	45.9	40.7	42.6	195
2	24.2	22.3	23.0	240	40.6	36.4	37.9	225
3	22.8	19.8	20.9	230	39.8	31.6	34.6	160
	COMPUTED							
1	26.23	23.96	24.75	288	46.64	40.82	42.96	175
2	24.08	22.40	23.02	245	40.70	96.36	37.92	150
3	22.55	19.81	20.81	233	40.37	31.83	34.97	145

$TC1_0$, $TC2_0$ = values of tank I and tank II temperatures at the beginning

$TC1_\infty$, $TC2_\infty$ = ultimate values of tank I and tank II temperatures

$TC1_{\tau_1}$, $TC2_{\tau_2}$ = value of tank I and tank II temperatures after one time constant elapsed.

τ_1, τ_2 = time constants for tank I and tank II, respectively.

5.B COMPUTER ANALYSIS OF DATA

Two iterative computer programs for both single tank and two tanks in series were developed. Calculations were made in three stages. In contrast to the approach used for experimental calculations, first external and internal film heat transfer coefficients (Chapter 2.B, Eq. 2.6, 2.7, 2.9) were calculated using the empirical equations. Since a dimensionally similar system to Cumming-West [19]; was used to calculate external film heat transfer coefficient, Cumming-West's empirical approach was chosen

(i.e. $HO{:}1.01(K/D_T)(ND_A^2\rho/\mu)^{0.62}(C_p\mu/K)^{1/3}(\mu/\mu_w)^{0.14}$).

Secondly overall heat transfer coefficient as calculated by combining the three series resistances (inside coefficient, tube wall, and outside coefficient). Eq. 2.2 was used neglecting fouling factors and with thin wall assumption (i.e. $1/U = (1/HI)+(1/HO)+(x/K_w)$), and the third stage deals with calculation of temperatures for both steady-state and unsteady-state cases.

Comparison of computed temperatures and experimentally observed temperatures for steady case are given in Appendix I and Tables A.I.1 through A.I.4.

Also computed external, internal and overall heat transfer coefficients with those of graphically found from the experimental data are given in Tables 5.3 through 5.6.

As an example of unsteady state case computed temperature-time results are given in Table 5.2.

For example steady-state case for single tank in Table 5.4 (run: 9) at N_{Re}: 29110 (agitated side) external film coefficient was calculated to be $W/m^2 °C$ (784 Btu/hr.sq ft.°F) and internal film coefficient at N_{Re} = 4800 (inside the coil) is 3284 $W/m^2 °C$ (578 Btu/hr.sq ft.°F).

Thermal resistance of tube, in Eq. 2.2 is x/K_w. The thermal conductivities of the tube wall was taken as 386 W/m °C [6] for copper.

The physical properties of water (C_p, μ, k, ρ) as a function of temperature as given in Appendix IV.

VI. DISCUSSION

6.A A DISCUSSION OF RESULTS AND FURTHER SUGGESTIONS

The system used in this investigation is a system that is dimensionally similar to that used by Cumming-West [19].

Cumming-West's correlation for heating and cooling fluids in a vessel with a single coil as heat transfer surface is given in Table 2.2, i.e. $HO = 1.01(D_T)^{-1}k(D_A{}^2N\rho/\mu)^{0.62}(C_p\mu/k)^{0.33}(\mu/\mu_W)^{0.14}$.

The individual film heat transfer coefficients were calculated from the experimental overall coefficients by using the Modified-Wilson graphical method and two computer programs were developed for computing film heat transfer coefficients and temperatures. These computed values were compared with the values obtained experimentally. It was reconfirmed that using the geometry factor "1.40", as pointed out by Ackley [24] instead of "1.01" gave better results as shown by the sample calculation in Table 6.1. The calculated values of "HO" from the correlation agree within experimental error with the value of "HO" from Wilson's graphical method. Hence the method of interpretation used appears to be sound for the data obtained. Film heat transfer coefficients for the various conditions of testing and for the steady-state case are given for both the single tank and two tanks in series in Tables 5.3 through 5.6.

TABLE 6.1 - Comparison of Geometry Factors With Experimental Results (SINGLE TANK)

Run	TC1 °C	TC2 °C	HI $W/m^2 °C$	HO $W/m^2 °C$	U $W/m^2 °C$
Geometry factor: 1.01					
11	43.04	52.70	7031	3410	2167
12	43.48	51.05	5725	3405	2023
13	39.77	47.15	4965	3328	1894
14	30.24	35.36	2766	3115	1411
15	28.69	31.80	1922	3060	1145
Geometry factor: 1.40					
11	44.42	51.64	6088	4738	2492
12	44.57	50.15	5693	4726	2420
13	40.70	46.15	4932	4613	2244
14	30.68	34.46	2744	4303	1605
15	28.86	31.18	1909	4225	1274
Experimental results					
11	44.8	51.2	6663	4219	2420
12	44.1	50.3	5487	4219	2246
13	40.7	46.3	4815	4219	2124
14	30.9	34.9	2870	4219	1635
15	29.0	30.9	2062	4219	1337

The model for heat transfer in two consecutive stirred tanks give result which are in agreement with experimental results.

Unsteady state experimental results are presented in Table 5.1 and Figure 5.13 and in Appendix I, Tables A.I.5 through A.I.9 and on Figures A.I.1 through A.I.5. As shown in the figures for single tank $Alpha_1$ and for two tanks in series Alpha and Beta remained almost constant, i.e. the convective heat transfer coefficient for unsteady-state conditions has the same value as for steady-state conditions.

The values of the individual film heat transfer coefficients found in this study were in agreement with the previously published values [17] and [19] for similar cases as shown in Figure 6.1.

In this investigation, a Reynolds Number range of 19,439 to 76,727 has been used for the agitated side, which is a region that has not been investigated much until today. In the coil side the range of Reynolds numbers was 1100 to 14000. For low velocities, i.e. expected laminar flow and transition region, theoretically obtained temperatures were highly different from the experimentally obtained. This problem was solved using the equation applicable to turbulent region for low velocities too. A sample is shown in Table 6.3. It is concluded that because of the geometric effects, turbulent flow is observed even for low Reynolds numbers.

The effect of agitator speed on the heat transfer coefficient is shown on Figures 5.11 and 5.12. It could be reasoned that higher agitation speeds up to a certain value should produce higher heat transfer coefficients and this was found to be true in both cases for single tank and two tanks in series.

TABLE 6.2 - Determination of Geometry Constant (Fig. 6.1)
(SINGLE TANK)

Run	$^{*}N_{Re} = \frac{D_A^2 N\rho}{\mu}$	$Y = \frac{(H_o D_T/k)(\mu_w/\mu)^{0.14}}{(C_p\mu/k)^{0.33}}$	C
1	33490	886	1.39
2	64300	1341	1.40
3	69200	1361	1.36
4	73500	1459	1.40
5	37100	941	1.39
6	35221	929	1.40
7	32121	860	1.38
8	31815	849	1.37
9	28709	788	1.37
10	24562	732	1.39
11	34100	920	1.42
12	34685	912	1.40
13	32571	882	1.40
14	26600	762	1.38
15	25834	760	1.40
16	30023	767	1.30
17	26812	745	1.34
18	26003	741	1.37
19	24151	720	1.38
20	22409	698	1.40

TABLE 6.2 - Continued... (TWO TANKS IN SERIES)

Run	TANK I			TANK II		
	N^*_{Re}	Y	C_1	N^*_{Re}	Y	C_2
21	21842	686	1.40	2985	823	1.38
22	31009	855	1.40	42826	1022	1.37
23	49862	1123	1.37	67841	1327	1.34
24	57248	1218	1.37	76727	1478	1.38
25	26630	776	1.40	38039	963	1.39
26	25364	766	1.42	35467	944	1.41
27	25072	756	1.41	35339	939	1.42
28	23900	740	1.42	33112	900	1.41
29	22895	721	1.42	31780	875	1.41
30	26033	769	1.40	32309	875	1.40
31	25074	762	1.42	30824	862	1.42
32	24300	746	1.42	30114	843	1.40
33	23355	722	1.41	29638	831	1.40
34	22711	711	1.41	28620	816	1.41
35	22053	685	1.39	28861	801	1.37
36	21472	677	1.40	27646	793	1.39
37	20609	660	1.40	25767	769	1.40
38	20086	648	1.39	24544	751	1.42
39	19439	635	1.39	23868	729	1.40

*Modified Reynolds number

C Geometry constant

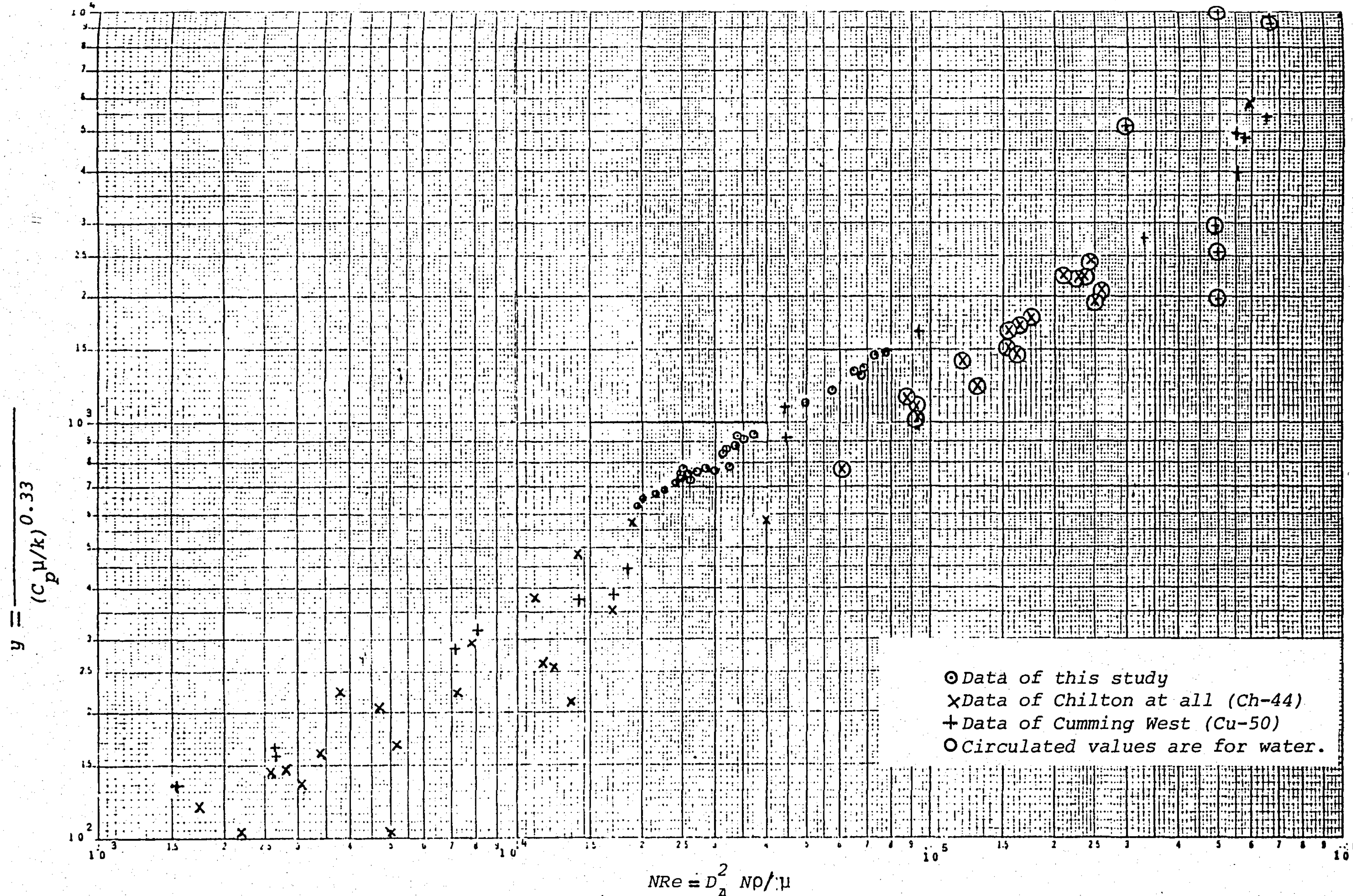


Figure 6-1.Final correlation of data with previous reported data

TABLE 6.3 - Sample Comparison Between Observed Temperatures and Calculated Temperatures (TWO TANKS IN SERIES)

Run	$N^*_{Re_{tank\ I}}$	$N_{Re_{tank\ II}}$	TC1	TC2	TH2	TH3
Experimentally observed temperatures						
25	5506	7959	30.9	49.5	53.7	33.9
26	4159	6294	27.6	45.6	49.6	29.9
27	4018	6145	27.3	45.4	48.1	29.5
28	2068	3419	22.1	36.6	38.8	22.9
29	1352	2327	20.1	31.1	32.9	20.8
Calculated results using laminar and transition regions equations						
25	6913	8545	26.77	37.45	64.95	51.38
26	5351	6849	25.56	35.72	62.50	47.81
27	5190	6682	25.57	35.74	62.62	47.64
28	2708	3815	22.84	31.27	54.29	38.08
29	1732	2610	21.24	28.61	48.59	32.23
Calculated results using turbulent region equations						
25	5402	8002	30.38	49.09	53.36	34.61
26	4080	6296	27.55	45.24	49.11	30.93
27	3998	6205	27.36	45.04	48.86	30.65
28	2067	3421	22.34	35.96	38.69	24.04
29	1360	2330	20.23	31.23	33.27	21.25

*Coil side.

During the experiments no measurements were made of coil wall temperatures; hence no direct data are available for the temperature difference between the coil wall and mixed water. But in computer programs wall temperatures were estimated to calculate viscosity at wall temperatures.

Equation of Cumming-West [19] and Chilton et.al [17] (Table 2.2) incorporate all the apparatus dimensions in the geometric constant 1.01 and 0.87 respectively which therefore restrict their application to apparatus geometrically similar to their experimental equipment. It is of interest to note that the exponentials of the Reynolds Number and Prandtl Number are not only constant in any given system, but seem to change very little with widely different mixing systems (Table 2.2, Chapter 2). If this conclusion can be substantiated, a greatly simplified approach to mixing heat transfer problems will be indicated.

The systems used in the present work were small. In scaling up heat transfer systems, all the different quantities that can be used to describe flow pattern and mixing performance are numerically different from a small to a large system. It is, therefore, important to carefully consider the effect of each these variables on scale-up and to make sure that, these adjustments are made properly. Further work on large scale apparatus is needed to check the film heat transfer equation.

The following work seems to desirable in this area of heat transfer.

1. to obtain generalized correlation for external film heat transfer coefficient, extensive available data with numerical and computer techniques.

2. to study the effect of finned coil geometry on external film heat transfer coefficient.

3. to determine the effect of agitator speed and type on external film heat transfer coefficient for finned-coiled tank.

4. to obtain additional experimental data using different liquids in agitated side of tank.

6.B DISCUSSION OF ERRORS

Any experimentally determined quantity is subject to error and hence any calculated result which is based on experimental evidance is also limited in accuracy. The determination of the derived error from the observed error is a calculation of some importance since it indicates the point where experimental technique should be improved.

There are many sources of error. For this study sources of errors can be classified as follows:

1. Errors of measurement
2. Precision errors

The first type of errors are due to physical limitations of reading scales. In this study this type of error arised from measurements of diameters (tank, coil, coil tube agitator), flowrates and agitator speed. Precision error are the "built in" errors of the apparatus, this type of errors arised from uncalibrated scale on digital thermometer and graduated cylinder. For example the digital thermometer was capable of measuring temperature to one decimal point.

All of above errors can only be estimated and rarely measured. Estimated values of errors are given below (Estimation of length were dependent on measurement made at least five different points).

Absolute error in diameter of agitator (δD_A)	:	0.01 cm
Absolute error in diameter of coil tubing (δD_H)	:	0.01 cm
Absolute error in diameter of coil (δD_c)	:	0.20 cm
Absolute error in diameter of tank (δD_T)	:	0.10 cm
Absolute error in agitator speed (δN)	:	3 rpm
Absolute error in hot water flowrate (δW)	:	0.05 ml/sec
Absolute errors in temperatures (δT)	:	0.4°C
Absolute errors in coil outside wall temperature (δT_w)	:	0.5°C

In the following part of this chapter, a general functional relationship for the film heat transfer coefficient in agitated side of vessel and in the coil side is developed to calculate the error margin.

Empirical equation used to calculate the film heat transfer coefficient in agitated side of the vessel is,

$$HO = 1.40(D_T)^{-1}k(\frac{D_A^2N\rho}{\mu})^{0.62}(\frac{C_p\mu}{k})^{0.33}(\frac{\mu}{\mu_w})^{0.14} \qquad (6.1)$$

where;

$$\rho = f(T), \quad \mu = f(T), \quad C_p = f(T), \quad \mu_w = \mu(T_w)$$

and external film coefficient is a function of below variables.

$$HO = f(D_T, D_A, N, T, T_w)$$

In the simplified form of equation (6.1)

$$HO = 1.40D_c^{-1}k^{0.77}D_A^{1.24}N^{0.62}\rho^{0.62}C_p^{0.33}\mu_w^{-0.14}\mu^{-0.15} \qquad (6.2)$$

so;

$$HO = HO' + \delta HO$$

$$D_T = D_T' + \delta D_c$$

$$D_A = D_A' + \delta D_A$$

$$N = N' + \delta N$$

$$T_w = T_w' + \delta T_w$$

$$T = T' + \delta T$$

HO, D_c, D_A, N, T_w, T = Poorest acceptable readings

$HO', D_T', D_A', N', T_w', T'$ = Unknown true values

$\delta HO, \delta D_c, \delta D_A, \delta N, \delta T_w, \delta T$ = Absolute errors in HO, D_c, D_A, N, T_w, and T respectively.

Taking the partial derivatives of Eq. (6.2) final equation to calculate error margin can be written as (Appendix V)

$$\frac{\delta HO}{HO} = \left|-\frac{\delta D_T}{D_T}\right| + \left|1.24\frac{\delta D_A}{D_A}\right| + \left|0.62\frac{\delta N}{N}\right| +$$

$$\left|-0.14(\mu_w)'\frac{\delta T_w}{\mu_w}\right| + \left|0.77(k)'\frac{\delta T}{k}\right| + \left|0.62(\rho)'\frac{\delta T}{\rho}\right|$$

$$+ \left|0.33(C_p)'\frac{\delta T}{C_p}\right| + \left|-0.15(\mu)'\frac{\delta T}{\mu}\right|$$

where;

$(k)'$, $(C_p)'$, $(\rho)'$, $(\mu)'$, $(\mu_w)'$ are derivatives.

Empirical equations used to calculate film heat transfer coefficient inside the coil is;

$$HI = 0.023k\, D_H^{-1}(C_p\mu/k)^{0.33}(D_H V_H/\mu)^{0.8}(\mu/\mu_w)^{0.14}(1 + 3.5(D_H/D_c))$$

$$(V_H = W/3.1414(D_H^2/4))$$

$$HI = 0.028k^{0.77}\mu^{-0.33}C_p^{0.33}\mu_w^{-0.14}D_H^{-1.8}W^{0.8} + 0.028(3.5)k^{0.77}\mu^{-0.33} \cdot C_p^{0.33}\mu_w^{-0.14}D_c^{-1}W^{0.8} \qquad (6.3)$$

$$HI = f_1(D_H, W, T, T_w) + f_2(W, D_c, T_w, T, D_H)$$

taking partial derivative of Eq. (6.3) the following equation is finally developed to calculate error (Appendix V).

$$\delta HI = HI[|0.8(\delta W/W)| + |-0.14(\mu_w)'(\delta T_w/\mu_w)| + |0.33(C_p)'(\delta T/C_p)| + |0.77(k)'(\delta T/k)| + |0.33(\mu)'(\delta T/\mu)| + |-0.8(\delta D_H/D_H|] + |0.028k^{0.77}\mu^{-0.33}C_p^{0.33}\mu_w^{-0.14}W^{0.8}D_H^{-1.8}(-\delta D_H/D_H) + 0.098k^{0.77}C_p^{0.33}\mu^{-0.33}\mu_w^{-0.14}W^{0.8}D_H^{-0.8}D_c^{-1}(-\delta D_c/D_c)|$$

Numerical error values depending on the estimated error values are given on Table 6.4.

TABLE 6.4 - Numerical Error Values

Run	δHI(±)	δHI%	δHO(±)	δHO%	δU(±)	δU%
SINGLE TANK						
1	23.7	0.35	61.9	1.32	22.2	0.8
2	23.2	0.34	61.4	0.88	17.5	0.5
3	22.6	0.34	62.3	0.81	16.6	0.5
4	22.6	0.34	63.0	0.77	16.2	0.4
5	30.0	0.41	63.4	1.29	23.9	0.8
6	22.6	0.34	62.8	1.31	21.9	0.8
7	9.0	0.17	61.6	1.32	17.3	0.7
8	0.8	0.02	61.2	1.32	13.5	0.6
9	13.9	0.42	59.6	1.34	13.9	0.7
10	30.6	1.73	56.5	1.35	18.8	1.5
11	25.7	0.37	62.3	1.32	22.8	0.8
12	12.3	0.21	62.1	1.31	18.5	0.7
13	4.7	0.10	61.2	1.32	15.4	0.6
14	18.2	0.66	58.1	1.35	14.3	0.8
15	27.8	1.45	57.2	1.36	17.5	1.3
16	20.3	0.32	60.0	1.34	21.1	0.8
17	3.7	0.08	58.8	1.34	14.7	0.6
18	2.8	0.07	58.6	1.34	12.9	0.6
19	16.5	0.63	56.1	1.36	13.5	0.8
20	25.7	1.45	54.7	1.36	16.4	1.3
TWO TANKS IN SERIES						
TANK I						
21	22.5	0.69	54.1	1.36	16.2	0.95
22	22.6	0.70	53.9	1.10	15.1	0.82
23	22.4	0.69	55.7	0.85	14.4	0.70
24	22.5	0.69	57.1	0.81	14.5	0.69
25	28.7	0.73	57.6	1.35	19.0	0.97
26	22.4	0.70	56.5	1.36	16.3	0.94
27	21.7	0.69	56.5	1.36	15.9	0.93
28	11.7	0.60	54.4	1.37	10.4	0.83
29	7.5	0.53	53.5	1.37	7.4	0.73
30	25.6	0.71	55.8	1.36	17.6	0.96
31	20.6	0.68	54.9	1.36	15.4	0.93
32	14.9	0.65	53.9	1.37	12.3	0.88
33	11.4	0.60	53.3	1.37	10.2	0.83
34	7.1	0.52	52.6	1.37	7.1	0.73

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TABLE 6.4 - Continued...

Run	δHI(±)	δHI%	δHO(±)	δHO%	δU(±)	δU%
35	24.3	0.70	54.2	1.36	17.0	0.96
36	19.6	0.68	53.6	1.37	14.8	0.93
37	14.5	0.64	52.7	1.37	12.0	0.88
38	11.5	0.61	52.2	1.37	10.2	0.83
39	6.8	0.52	51.4	1.37	6.8	0.72
TANK II						
21	31.3	0.77	59.9	1.33	19.9	0.98
22	31.5	0.77	59.4	1.07	18.7	0.85
23	30.5	0.76	60.7	0.83	17.8	0.73
24	30.3	0.75	61.7	0.78	17.8	0.72
25	39.7	0.82	63.2	1.30	22.7	1.00
26	31.7	0.79	62.3	1.31	20.0	0.97
27	30.8	0.79	62.3	1.31	19.7	0.97
28	17.0	0.68	59.6	1.34	13.5	0.88
29	11.0	0.60	58.1	1.35	9.9	0.80
30	34.1	0.78	60.9	1.33	20.9	0.99
31	28.2	0.76	60.3	1.34	18.7	0.96
32	20.4	0.70	58.5	1.35	15.3	0.92
33	15.8	0.66	57.8	1.35	12.9	0.87
34	10.0	0.58	56.4	1.36	9.2	0.78
35	30.9	0.75	59.0	1.34	19.8	0.98
36	25.3	0.73	58.4	1.35	17.5	0.95
37	18.8	0.68	57.2	1.35	14.5	0.91
38	15.1	0.65	56.3	1.36	12.4	0.87
39	9.0	0.56	54.8	1.36	8.5	0.76

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APPENDICES

APPENDIX I

EXPERIMENTAL DATA AND COMPUTED TEMPERATURES

SYMBOLS USED

SINGLE TANK

TCO: Cold water inlet temperature (°C)

TH1: Hot water inlet temperature (°C)

TC1: Cold water exit temperature (°C)

TH2: Hot water exit temperature (°C)

TWO TANKS IN SERIES

TCO: Cold water inlet temperature to tank I (°C)

TH1: Hot water inlet temperature to tank II (°C)

TC1: Cold water exit temperature from tank I (°C)

TC2: Cold water exit temperature from tank II (°C)

TH2: Hot water exit temperature from tank II (°C)

TH3: Hot water exit temperature from tank I (°C)

TABLE A.I.1 - Agitator Speed is Variable - Single Tank - Steady State

						Observed Temperatures		Computed Temperatures	
Run	N (rpm)	W (ml/sec)	M (ml/sec)	TH1 (°C)	TCO (°C)	TC1 (°C)	TH2 (°C)	TC1 (°C)	TH2 (°C)
1	200	26.5	22.3	75.6	12.6	41.6	50.5	42.35	50.36
2	380	26.5	22.5	75.7	12.5	42.9	49.3	43.48	49.19
3	450	26.3	22.5	75.5	12.6	43.5	49.0	43.60	48.79
4	500	26.5	23.5	75.0	12.6	42.2	47.9	42.88	47.95

TABLE A.I.2 - Hot Water Flowrate is Variable - Single Tank - Steady-State

						Observed Temperatures		Computed Temperatures	
Run	W (ml/sec)	TH1 (°C)	M (ml/sec)	N (rpm)	TCO (°C)	TC1 (°C)	TH2 (°C)	TC1 (°C)	TH2 (°C)
5	27.5	83.5	19.2	200	11.3	48.5	57.0	48.92	57.01
6	25.0	81.2	18.5	200	8.9	45.0	53.5	45.72	53.72
7	19.8	80.0	19.0	200	8.5	41.5	47.9	41.34	48.20
8	16.0	82.2	19.5	200	10.3	40.0	45.7	39.88	45.81
9	11.2	81.5	20.5	200	12.1	34.6	38.9	34.89	39.38
10	5.6	80.1	20.0	200	12.1	26.3	28.2	26.33	28.73
11	27.5	73.5	21.0	200	16.0	44.8	51.2	44.42	51.64
12	21.5	73.3	18.0	200	17.1	44.1	50.3	44.57	50.15
13	18.5	72.5	20.0	200	16.5	40.7	46.3	40.70	46.15
14	9.6	73.5	20.0	200	12.1	30.9	34.9	30.68	34.46
15	6.3	72.1	22.5	200	17.5	29.0	30.9	28.86	31.18
16	27.1	62.8	19.5	200	10.0	36.9	43.4	36.56	43.57
17	19.0	62.3	20.2	200	10.9	33.2	38.4	32.93	38.72
18	16.1	62.9	19.0	200	11.3	33.0	37.1	32.58	37.62
19	10.0	60.3	20.0	200	10.1	25.8	28.8	25.50	29.28
20	6.4	60.6	20.0	200	10.3	22.8	24.0	21.79	24.42

TABLE A.I.3 - Agitator Speed is Variable - Two Tanks in Series - Steady-State

						Observed Temperatures				Computed Temperatures			
Run	N (rpm)	W (ml/sec)	M (ml/sec)	TH1 (°C)	TC0 (°C)	TC1 (°C)	TC2 (°C)	TH2 (°C)	TH3 (°C)	TC1 (°C)	TC2 (°C)	TH2 (°C)	TH3 (°C)
21	200	15.0	30.2	73.4	12.2	20.8	36.6	41.7	25.1	20.52	36.25	41.48	24.60
22	280	15.0	30.0	74.5	12.8	21.3	37.4	42.0	24.4	21.27	37.50	41.80	24.72
23	450	15.1	30.0	71.0	12.3	21.0	36.5	40.1	23.9	21.34	36.79	40.07	24.00
24	500	15.0	30.0	70.3	15.3	22.8	37.1	39.6	25.1	22.92	37.66	40.61	25.28

TABLE A.I.4 - Hot Water Flowrate is Variable - Two Tanks in Series - Steady-State

						Observed Temperatures				Computed Temperatures			
Run	W (ml/sec)	TH1 (°C)	M (ml/sec)	N (rpm)	TC0 (°C)	TC1 (°C)	TC2 (°C)	TH2 (°C)	TH3 (°C)	TC1 (°C)	TC2 (°C)	TH2 (°C)	TH3 (°C)
25	16.6	80.6	24.0	200	17.5	30.9	49.5	53.7	33.9	30.38	49.09	53.36	34.61
26	13.5	80.8	24.0	200	17.4	27.6	45.6	49.6	29.9	27.55	45.23	49.11	30.94
27	13.1	81.5	24.0	200	17.5	27.3	45.4	48.1	29.5	27.36	45.04	48.86	30.65
28	8.0	79.9	24.0	200	17.5	22.1	36.6	38.8	22.9	22.34	35.96	38.68	24.04
29	5.7	80.0	24.0	200	17.4	20.1	31.1	32.9	20.8	20.23	31.22	33.27	21.25
30	16.2	71.0	28.0	200	16.2	26.6	40.8	44.9	30.6	25.25	40.28	44.87	29.11
31	13.4	72.8	28.0	200	15.8	23.5	38.8	41.7	26.1	23.24	37.83	42.09	26.44
32	10.2	71.2	28.0	200	15.9	19.8	32.5	36.8	22.8	20.88	33.30	36.84	23.08
33	8.2	71.3	28.0	200	15.8	18.9	30.1	33.1	20.6	19.40	30.41	33.43	21.03
34	5.7	71.1	28.0	200	15.9	17.9	26.7	28.7	18.6	17.89	26.46	28.67	18.80
35	16.5	60.7	27.0	200	12.5	21.4	34.8	39.4	24.4	20.99	34.31	38.97	24.81
36	13.5	61.7	27.0	200	12.9	19.5	31.8	35.8	21.3	19.67	32.27	36.36	22.73
37	10.4	61.2	27.0	200	12.9	17.9	28.9	32.8	19.2	17.65	28.73	32.25	19.84
38	8.6	60.9	27.1	200	12.8	16.1	25.6	29.8	18.1	16.38	26.30	29.41	18.07
39	5.7	60.4	27.0	200	12.9	15.3	22.3	24.1	15.6	14.76	22.28	24.52	15.66

TABLE A.I.5 - Temperature - Time Data - Observed

Set No. : 1 (Single tank)

N - Agitator speed : 200 rpm
W - Hot water flowrate : 18.5 ml/sec
M - Cold water flowrate: 20.0 ml/sec

TCO(1) : 14.2°C
TH1(1) : 81.3°C

TC1S	TH2S
43.4°C	49.1°C

TCO(2) : 14.2°C
TH2(2) : 67.0°C

Time sec	TC1 °C	TH2 °C	*$ALPHA_1$
30	41.8	45.9	0.162
60	40.7	44.9	0.160
90	40.0	44.3	0.159
120	37.5	43.8	0.156
150	38.9	43.5	0.163
180	38.0	43.1	0.164
210	37.8	42.9	0.169
240	37.7	42.7	0.168
270	37.5	42.5	0.164
300	37.4	42.2	0.159
330	37.3	42.1	0.159
360	37.2	42.0	0.158
390	37.1	41.9	0.158
420	37.0	41.9	0.161
450	37.0	41.8	0.160
480	36.9	41.8	0.160
510	36.9	41.7	0.159
540	36.9	41.7	0.159
570	36.9	41.7	0.159
600	36.9	41.7	0.159

*$ALPHA_1$ = (TH2 - TC1)/(TH1 - TC1)

TABLE A.I.6 - Temperature - Time Data - Observed

Set No. : 2 (Single tank)

N - Agitator speed : 200 rpm
W - Hot water flowrate : 20.0 ml/sec
M - Cold water flowrate: 20.0 ml/sec

TCO(1) : 13.7°C

TH1(1) : 69.0°C

TC1S	TH1S
38.7°C	43.9°C

TCO(2) : 13.7°C
TH1(2) : 59.8°C

Time sec	TC1 °C	TH2 °C	$ALPHA_1$
30	37.2	42.0	0.212
60	36.2	41.9	0.216
90	36.0	40.7	0.198
120	35.4	40.6	0.213
150	35.1	40.1	0.202
180	35.0	40.0	0.202
210	34.8	39.8	0.200
240	34.7	39.7	0.199
270	34.6	39.6	0.198
300	34.4	39.3	0.193
330	34.3	39.3	0.196
360	34.2	39.1	0.191
390	34.1	39.1	0.195
420	34.0	39.0	0.194
450	34.0	38.9	0.190
480	33.9	38.8	0.189
510	33.8	38.8	0.192
540	33.8	38.8	0.192
570	33.8	38.8	0.192
600			

TABLE A.I.7 - Temperature - Time Data - Observed

Set No. : 3 (Single tank)

N - Agitator speed : 200 rpm
W - Hot water flowrate : 20.0 ml/sec
M - Cold water flowrate: 20.0 ml/sec

TCO(1) : 12.9°C
TH1(1) : 83.8°C

	TC1S	TH2S
	44.7 °C	50.5 °C

TCO(2) : 12.9°C
TH1(2) : 63.5°C

Time sec	TC1 °C	TH2 °C	$ALPHA_1$
30	42.8	46.1	0.160
60	41.1	44.6	0.160
90	39.6	43.9	0.180
120	38.4	42.8	0.175
150	37.9	42.5	0.180
180	37.5	41.8	0.165
210	37.2	41.6	0.167
240	36.9	41.1	0.158
270	36.4	40.9	0.166
300	36.3	40.8	0.166
330	36.1	40.7	0.168
360	35.9	40.7	0.174
390	35.8	40.6	0.173
420	35.8	40.6	0.173
450	35.7	40.6	0.173
480	35.7	40.5	0.172
510	35.7	40.5	0.172
540	35.6	40.4	0.172
570	35.6	40.4	0.172
600	35.6	40.4	0.172

TABLE A.I.8 - Temperature - Time Data - Observed

Set No. : 2 (Two tanks in series)

N - Agitator speed : 200 rpm
W - Hot water flowrate : 15.5 ml/sec
M - Cold water flowrate: 24.0 ml/sec

TCO(1) : 13.2°C
TH1(1) : 71.0°C

TC1S	TC2S	TH2S	TH3S
24.2°C	40.6°C	45.3°C	27.7°C

TCO(2) : 13.2°C
TH1(2) : 61.8°C

Time sec	TC1 °C	TC2 °C	TH2 °C	TH3 °C	*ALPHA	*BETA
30	24.0	40.0	43.4	27.3	0.170	0.156
60	23.8	39.4	42.8	27.0	0.168	0.152
90	23.6	39.2	42.4	26.8	0.170	0.142
120	23.5	38.9	42.0	26.6	0.167	0.135
150	23.3	38.5	41.6	26.3	0.164	0.133
180	23.2	38.3	41.3	26.2	0.166	0.271
210	23.1	38.0	41.2	26.0	0.161	0.135
240	23.0	37.8	40.9	25.8	0.157	0.129
270	22.9	37.7	40.8	25.8	0.162	0.129
300	22.8	37.5	40.8	25.7	0.161	0.136
330	22.7	37.4	40.7	25.6	0.161	0.135
360	22.7	37.3	40.6	25.5	0.156	0.135
390	22.6	37.2	40.6	25.5	0.161	0.138
420	22.6	37.0	40.5	25.4	0.157	0.141
450	22.6	36.9	40.4	25.3	0.152	0.141
480	22.5	36.8	40.4	25.2	0.151	0.144
510	22.5	36.7	40.3	25.2	0.152	0.143
540	22.4	36.7	40.3	25.2	0.157	0.143
570	22.4	36.6	40.3	25.1	0.151	0.147
600	22.3	36.5	40.2	25.1	0.157	0.146
630	22.3	36.4	40.2	25.1	0.157	0.150
660	22.3	36.4	40.2	25.1	0.157	0.149
690	22.3	36.4	40.2	25.1	0.157	0.149

$$ALPHA = \frac{TH3 - TC1}{TH2 - TC1} \quad ; \quad BETA = \frac{TH2 - TC2}{TH1 - TC2}$$

TABLE A.I.9 - Temperature - Time Data - Observed

Set No. : 3 (Two tanks in series)

N - Agitator speed : 200 rpm
W - Hot water flowrate : 13.5 ml/sec
M - Cold water flowrate: 28.5 ml/sec

TCO(1) : 13.7°C
TH1(1) : 83.2°C

TC1S	TC2S	TH2S	TH3S
22.8°C	39.8°C	45.2°C	25.9°C

TCO(2) : 13.7°C
TH1(2) : 60.9°C

Time sec	TC1 °C	TC2 °C	TH2 °C	TH3 °C	ALPHA	BETA
30	22.4	38.5	41.3	25.4	0.159	0.125
60	22.1	37.2	40.1	25.1	0.167	0.122
90	21.8	35.9	39.3	24.7	0.166	0.136
120	21.6	35.2	38.7	24.3	0.158	0.136
150	21.4	34.7	38.1	24.1	0.162	0.129
180	21.2	34.2	37.7	23.8	0.157	0.131
210	21.1	33.7	37.2	23.7	0.162	0.128
240	20.8	33.4	37.1	23.2	0.148	0.134
270	20.7	33.2	36.9	23.1	0.148	0.133
300	20.5	33.0	36.6	22.9	0.149	0.129
330	20.4	32.8	36.4	22.9	0.156	0.128
360	20.3	32.6	36.3	22.8	0.156	0.130
390	20.2	32.5	36.2	22.7	0.156	0.131
420	20.1	32.3	36.1	22.6	0.156	0.133
450	20.1	32.2	36.0	22.6	0.157	0.133
480	20.0	32.0	35.8	22.5	0.158	0.131
510	20.0	31.9	35.7	22.5	0.159	0.131
540	19.9	31.8	35.6	22.4	0.159	0.131
570	19.9	31.7	35.4	22.4	0.161	0.127
600	19.8	31.7	35.3	22.3	0.162	0.123
630	19.8	31.6	35.3	22.3	0.162	0.126
660	19.8	31.6	35.3	22.3	0.162	0.126
690	19.8	31.6	35.3	22.3	0.162	0.126

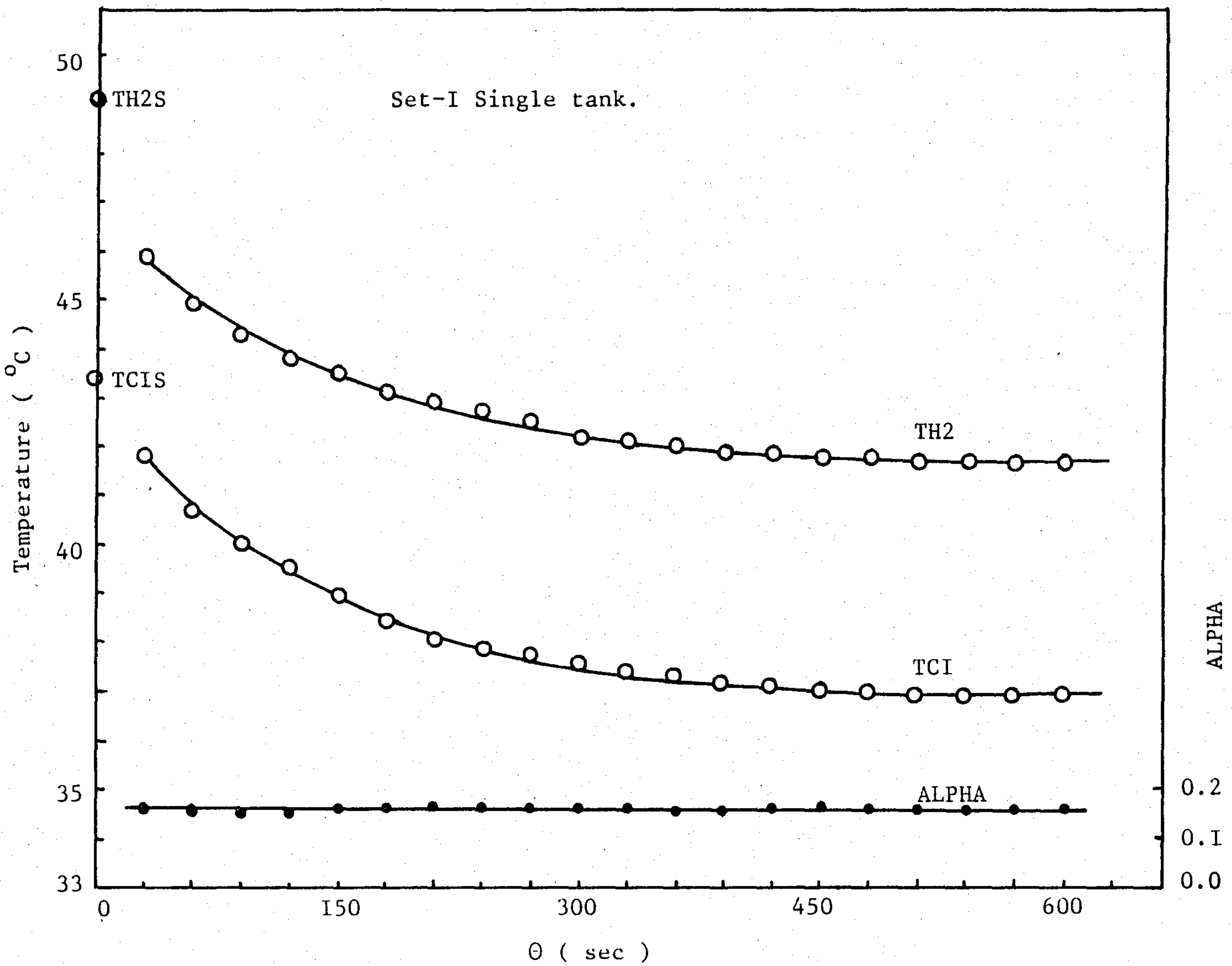

Figure A-I.I. Temperature change with time for unsteady-state heat transfer.

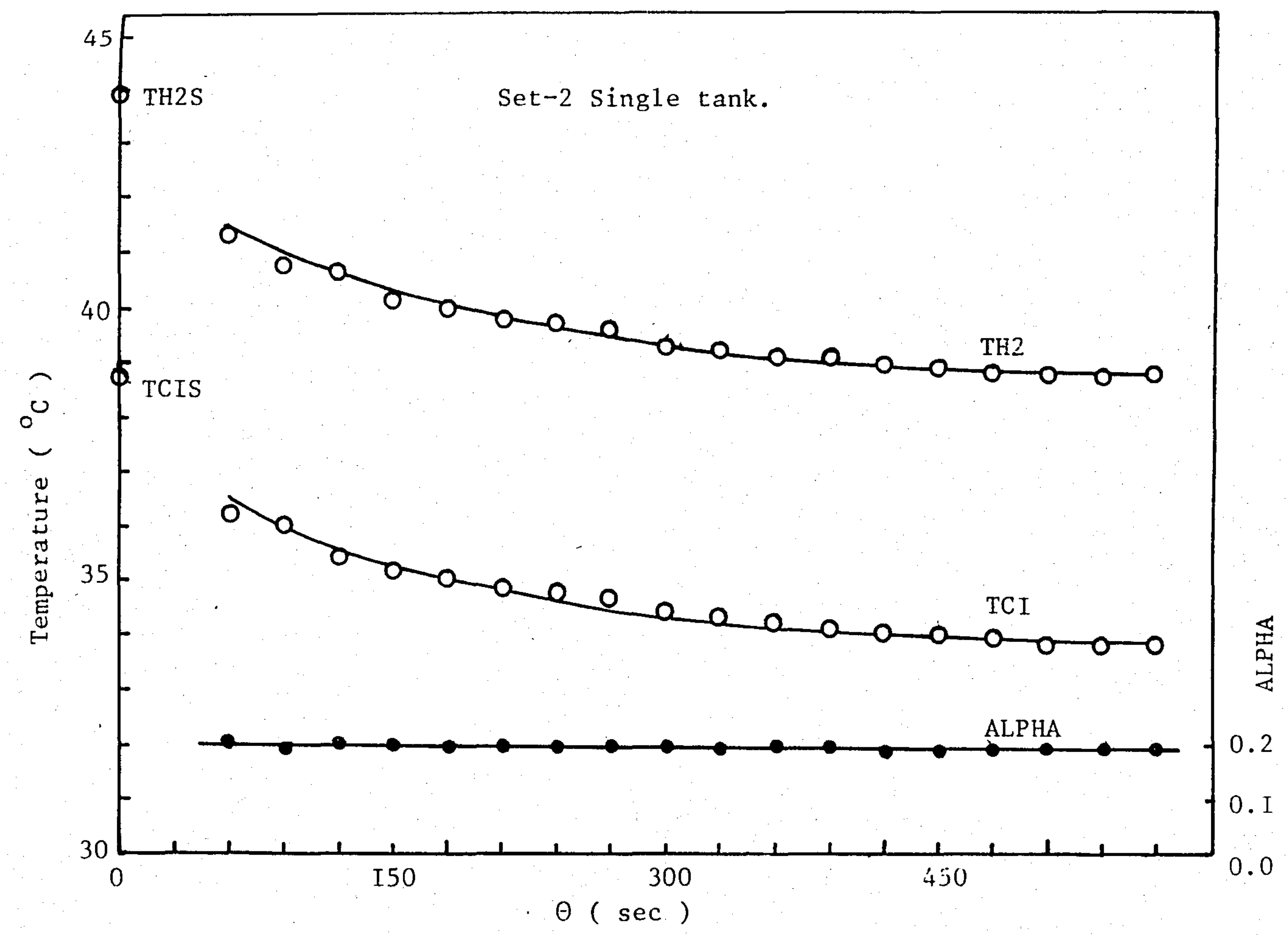

Figure A-I.2. Temperature change with time for unsteady-state heat transfer.

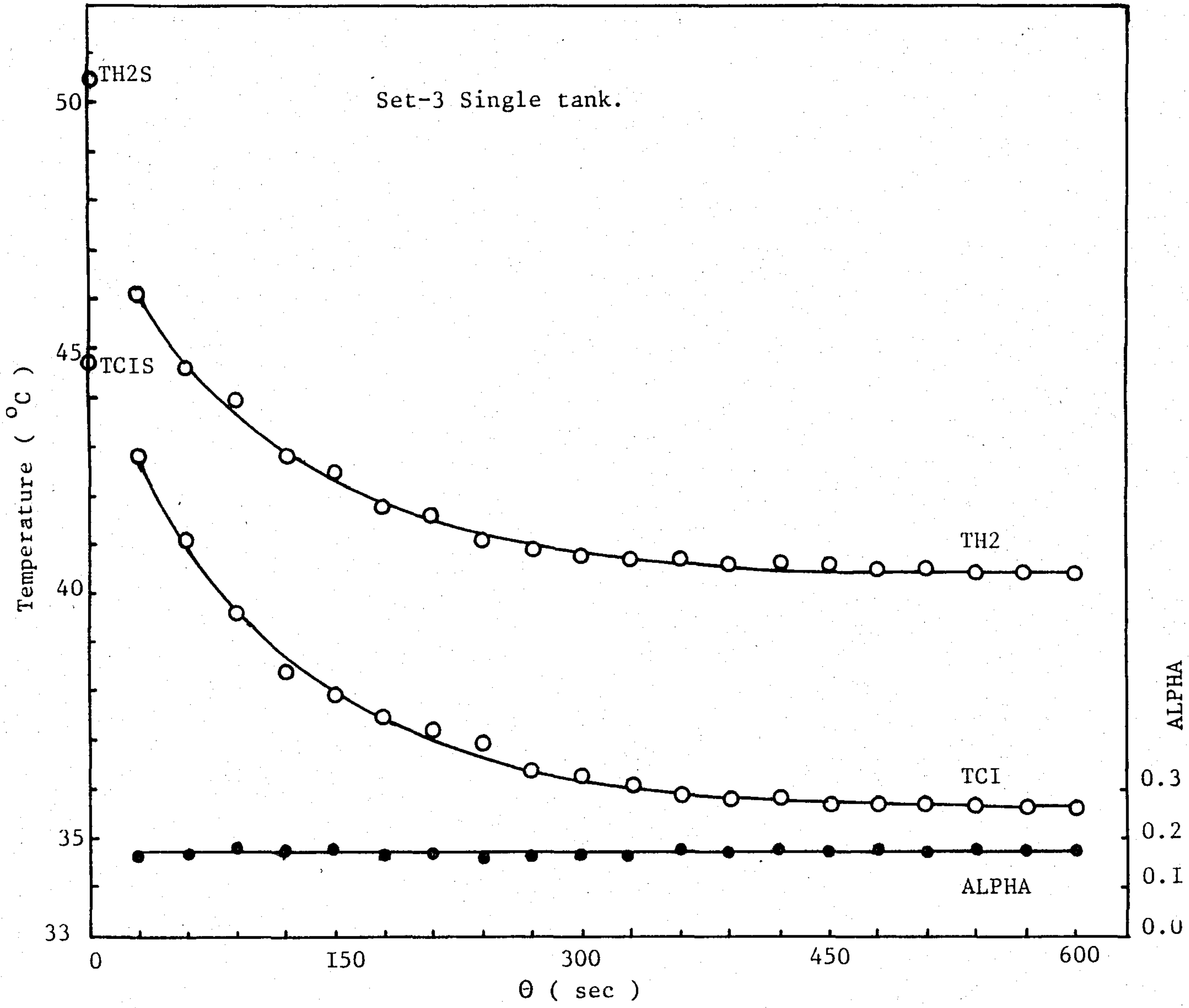

Figure A-I.3. Temperature change with time for unsteady-state heat transfer.

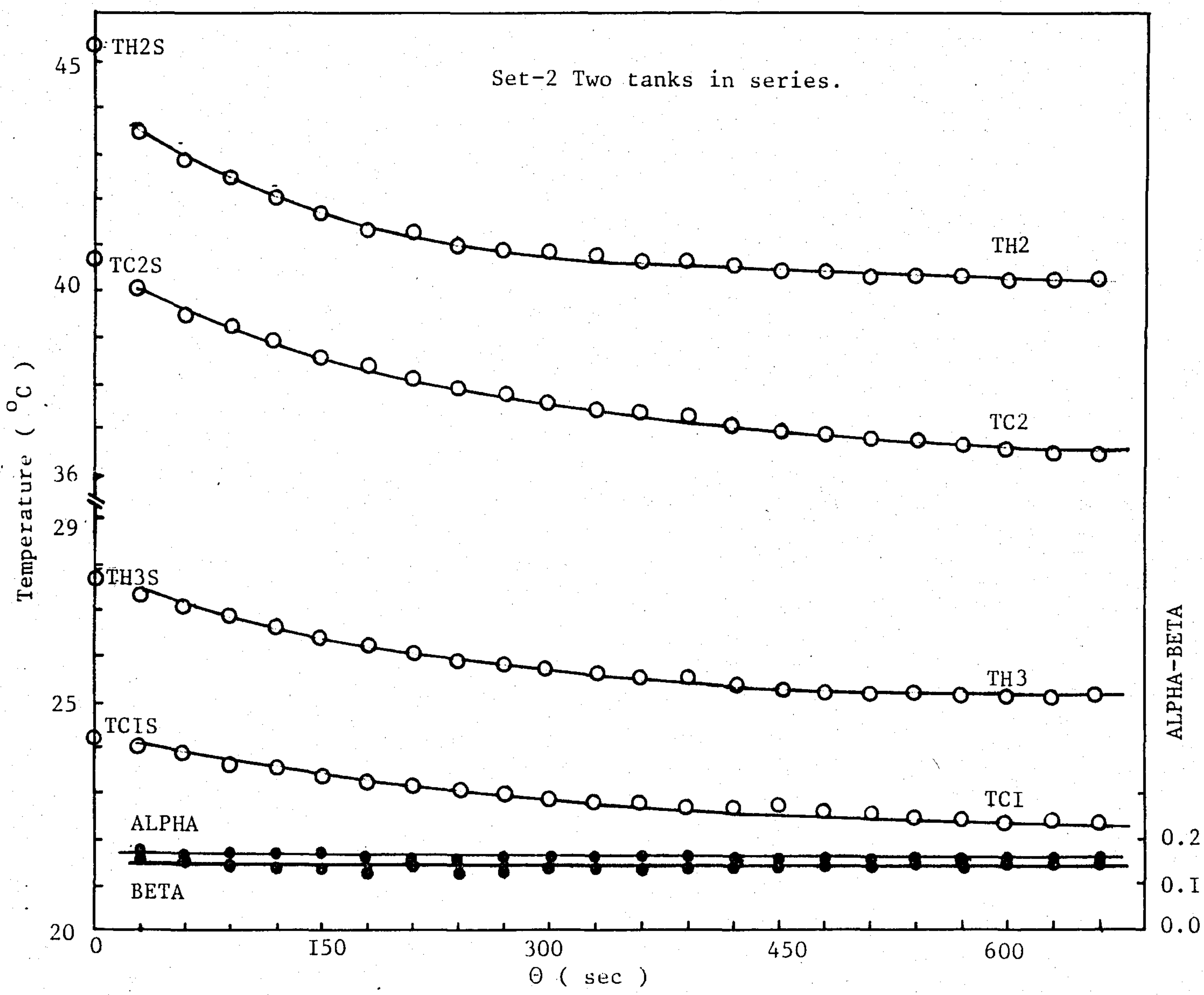

Figure A-I.4. Temperature change with time for unsteady-state heat transfer.

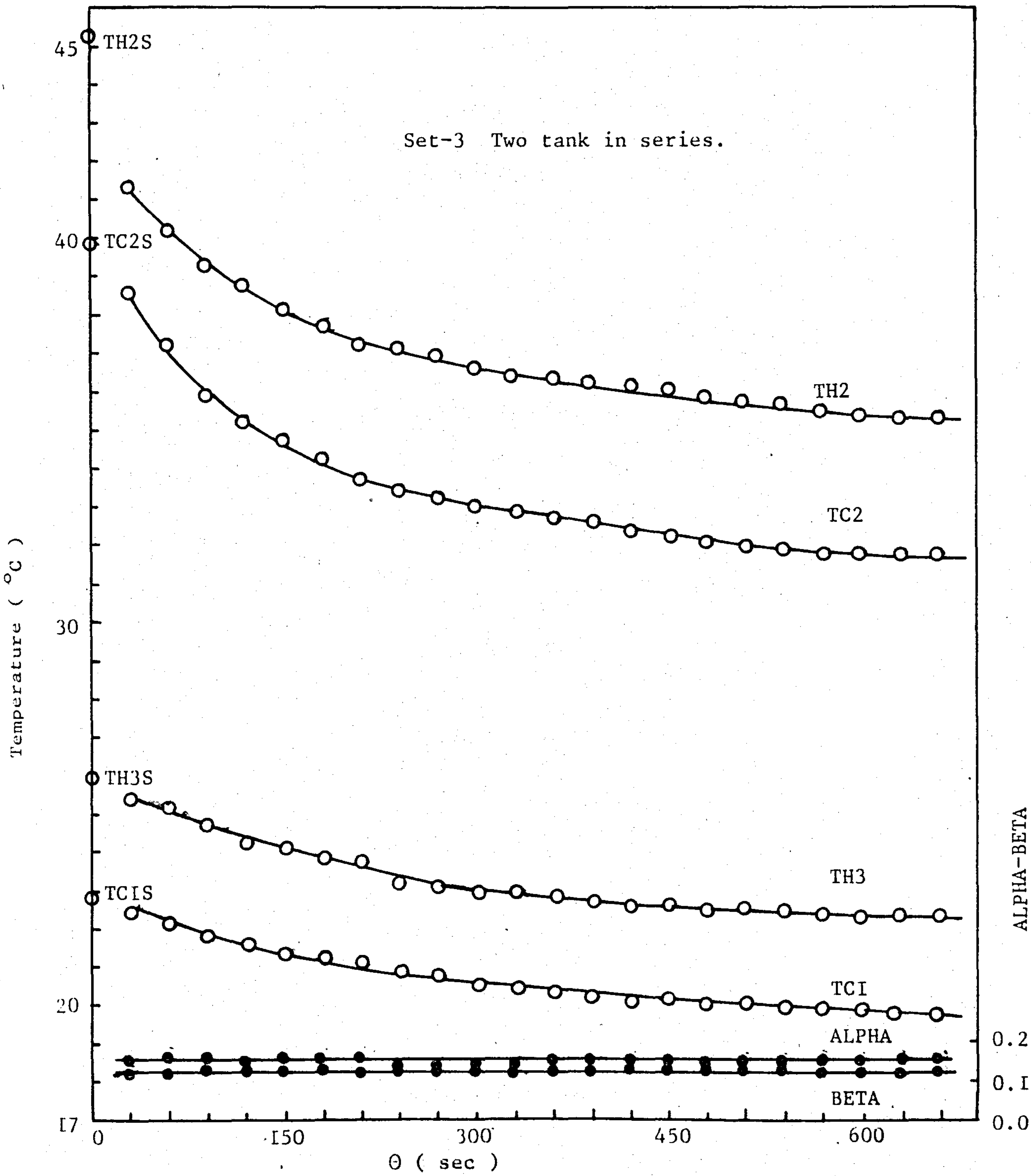

Figure A-I.5. Temperature change with time for unsteady-state heat transfer.

APPENDIX II

MATHEMATICAL MODELLING

A.II.1 MATHEMATICAL MODELLING FOR SINGLE TANK

As shown in Figure 3.1, flow of cold water was in the tank side and hot water in the coil side. Counter current was performed in this system.

Assuming $W = W.C_h \rho_h$, $M = M.C_w \rho_w$ and $V = V.C_w \rho_w$ heat balance is;

$$W\,T_1 - W\,T_2 + Mt_o - Mt_1 = V\,\frac{dt_1}{d\theta} \qquad \text{(A.2.1)}$$

Assuming proper agitation, (i.e. temperature in the tank, t_1) the heat transfer rate equation for the tank is

$$\frac{U_1 A (T_2 - T_1)}{\ln \dfrac{T_2 - t_1}{T_1 - t_1}} = W(T_1 - T_2)$$

or

$$\ln \frac{T_2 - t_1}{T_1 - t_1} = \exp[-\,U_1 A/W] = \alpha$$

$$T_2 - t_1 = \alpha(T_1 - t_1)$$

$$T_2 = \alpha T_1 - \alpha t_1 + t_1$$

$$T_2 = \alpha T_1 + (1 - \alpha)t_1 \qquad \text{(A.2.2)}$$

From Equation (A.2.1)

$$T_2 = \frac{WT_1 + Mt_o - Mt_1 - V(dt_1/d\theta)}{W}$$

$$WT_1 + Mt_o - Mt_1 - V(dt_1/d\theta) - W\,T_1 - W(1 - \alpha)t_1 = 0$$

First order linear equation with constant coefficients was obtained,

$$[M + W(1 - \alpha)]t_1 + V(dt_1/d\theta) = W(1 - \alpha)T_1 + Mt_o \qquad \text{(A.2.3)}$$

$$F = M + W(1 - \alpha)$$

$$H = W(1 - \alpha)T_1 + Mt_o$$

Equation (A.2.3) can be written as,

$$Ft_1 + V(dt_1/d\theta) = H$$

then;

$$Vm + F = 0 \qquad m = -F/V$$

And therefore complementary function is

$$t_1 = Ae^{m\theta}$$

$$t_1 = Ae^{-F/V\theta}$$

The right hand side of Equation (A.2.3) is a constant and therefore the particular integral is a constant and equal to right hand side of Equation (A.2.3) divided by the coefficient t_1, then particular solution;

$$t_{1p} = H/F = B$$

And the complete solution is;

$$t_1 = Ae^{m_1\theta} + B$$

where A is arbitrary constant, using following initial conditions it can be calculated

at $\qquad \theta = 0 \qquad t_1 = t_{1s}$

$$t_1 = [t_{1s} - H/F]e^{-F/V\theta} + \frac{H}{I}$$

inserting $W = WC_h\rho_h$, $M = MC_w\rho_w$, $V = VC_w\rho_w$ into above equation, final form is,

$$t_1 = [t_{1s} - \frac{WC_h\rho_h(1-\alpha)T_1 + MC_w\rho_w t_o}{MC_w\rho_w + WC_h\rho_h(1-\alpha)}]\exp^{((MC_w\rho_w+WC_h\rho_h(1-\alpha)/VC_w\rho_w)\theta}$$

$$- \frac{WC_h\rho_h(1-\alpha)T_1 + MC_w\rho_w t_o}{MC_w\rho_w + WC_h\rho_h(1-\alpha)} \qquad (A.2.4)$$

Using Equations (A.2.2) and (A.2.4), unknown temperatures can be calculated.

A.II.2 MATHEMATICAL MODELLING FOR TWO TANKS IN SERIES

As shown in Figure 3.2, heat balances for the two tanks in series are as follows. Again assume that $M = MC_w\rho_w$, $W = WC_h\rho_h$ and $V = VC_w\rho_w$.

Tank I $\quad WT_2 - WT_3 + Mt_o - Mt_1 = V(dt_1/d\theta)$ (A.2.5)

Tank II $\quad WT_1 - WT_2 + Mt_1 - Mt_2 = V(dt_2/d\theta)$ (A.2.6)

Heat transfer rate equations for the two tanks

Tank I $\quad \frac{T_3 - t_1}{T_2 - t_1} = \exp[-U_1A/W] = \alpha$

Tank II $\quad \frac{T_2 - t_2}{T_1 - t_2} = \exp[-U_2A/W] = \beta$

$$T_3 - t_1 = \alpha T_2 - \alpha t_1$$

$$T_2 - t_2 = \beta T_1 - \beta t_2$$

$$T_3 = \alpha T_2 + t_1(1 - \alpha) \qquad \text{(A.2.7)}$$

$$T_2 = \beta T_1 + t_2(1 - \beta) \qquad \text{(A.2.8)}$$

These four exuations (A.2.5), (A.2.6), (A.2.7), (A.2.8) have to be solved simultaneously. Frequency of appearance of variables

T_3	T_2	t_1	t_2
1	1	1	
1	1	+	+
	1	1	1
	1	1	1
2	4	3,+	2,+

+, shows differential form

T_3, must be eliminated first, then T_2 because t_1 and t_2 appear in a differentiated form substitution of Equation (A.2.7) into Eq. (A.2.5).

$$WT_2 - W(\alpha T_2 + t_1(1 - \alpha)) + Mt_o - MC_w = V(dt_1/d\theta)$$

$$WT_2 - W\alpha T_2 - Wt_1 + W\alpha t_1 + Mt_o - Mt_1 = V(dt_1/d\theta)$$

$$W(1 - \alpha)T_2 + Mt_o + (W\alpha - W - M)t_1 = V(dt_1/d\theta) \qquad \text{(A.2.9)}$$

now eliminate T_2 from the system by substituting from Equation (A.2.8) to Equations (A.2.9) and (A.2.6)

$$W(1 - \alpha)[\beta T_1 + T_2(1 - \beta)] + Mt_o + (W\alpha - W - M)t_1 = V(dt_1/d\theta)$$

$$W(1 - \alpha)\beta T_1 + W(1 - \alpha)(1 - \beta)t_2 + Mt_o + (W\alpha - W - M)t_1 = V(dt_1/d\theta) \qquad \text{(A.2.10)}$$

and

$$WT_1 - W[\beta T_1 + t_2(1 - \beta)] + Mt_1 - Mt_2 = V(dt_2/d\theta)$$

$$WT_1 - W\beta T_1 - W(1 - \beta)t_2 + Mt_1 - Mt_2 = V(dt_2/d\theta)$$

$$(W - W\beta)T_1 + Mt_1 - [W(1 - \beta) + M]t_2 = V(dt_2/d\theta)$$

$$t_1 = \frac{1}{M}[V(dt_2/d\theta) + ((W/M)(1 - \beta) + 1)t_2 + (W\beta - W)T_1]$$

$$t_1 = (V/M)(dt_2/d\theta) + [(W/M)(1 - \beta) + 1]t_2 + ((W/M)\beta - (WC_h/MC_w)T_1) \qquad \text{(A.2.11)}$$

$$\frac{dt_1}{d\theta} = \frac{V}{M}\frac{d^2t_2}{d\theta^2} + [(W/M)(1 - \beta) + 1]\frac{dt_2}{d\theta} \qquad \text{(A.2.12)}$$

using Equations (A.2.11) and (A.2.12) to eliminate t_1 and its differential coefficient from Equation (A.3.10)

$$W(1 - \alpha)\beta T_1 + W(1 - \alpha)(1 - \beta)t_2 + Mt_o + (W\alpha - W - M)[(V/M)(dt_2/d\theta)$$

$$+ [(W/M)(1 - \beta) + 1]t_2 + ((W/M)\beta - (W/M)T_1] =$$

$$W[(V/M)(d^2t_2/d\theta^2) + [(W/M)(1 - \beta) + 1](dt_2/d\theta)]$$

$$W(1 - \alpha)\beta T_1 + W(1 - \alpha)(1 - \beta)t_2 + Mt_o + \frac{VW}{M}\alpha \frac{dt_2}{d\theta} - \frac{W}{M}\frac{dt_2}{d\theta}$$

$$- \frac{W}{M}\frac{dt_2}{d\theta} - V\frac{dt_2}{d\theta} + [-\frac{W^2}{M}\alpha(1 - \beta) + W\alpha]t_2 + [\frac{W^2}{M}\alpha\beta - \frac{W^2}{M}\alpha]T_1$$

$$- [\frac{W^2}{M}\beta - \frac{W^2}{M}]T_1 - [W\beta - W]T_1 = \frac{V^2}{M}\frac{d^2t_2}{d\theta^2} + [\frac{VW}{M}(1 - \beta) + V]\frac{dt_2}{d\theta}$$

$$\frac{V^2}{M}\frac{d^2t_2}{d\theta} + [\frac{VW}{M}(1 - \beta) + W - \frac{VW}{M}\alpha + \frac{WV}{M} + V]\frac{dt_2}{d\theta} =$$

$$Mt_o + [W(1 - \alpha)\beta + \frac{W^2}{M}\alpha\beta - \frac{W^2}{M}\alpha + \frac{W^2}{M}(1 - \beta) + W(1 - \beta)]T_1$$

$$+ [W(1 - \alpha)(1 - \beta) + W\alpha + \frac{W^2}{M}\alpha(1 - \beta) - \frac{W^2}{M}(1 - \beta) - W$$

$$- W(1 - \beta) - M]t_2$$

$$\frac{V^2}{M}\frac{d^2t_2}{d\theta^2} + [2\frac{VW}{M} + 2V - \frac{VM}{M}\beta - \frac{VW}{M}\alpha]\frac{dt_2}{d\theta} =$$

$$Mt_o + [M\beta - W\alpha\beta + \frac{W^2}{M}\alpha\beta - \frac{W^2}{M}\alpha + \frac{W^2}{M} - \frac{W^2}{M}\beta + W - W\beta]T_1$$

$$+ [W - W\alpha - W\beta + W\alpha\beta + W\alpha - \frac{W^2}{M}\alpha - \frac{W^2}{M}\alpha\beta - \frac{W^2}{M} + \frac{W^2C_h^2}{M}\beta - W]$$

Second order linear differential equation with constant coefficients is obtained.

$$(V^2/M)(d^2t_2/d\theta^2) + [2(VW/M) + 2V - (VW/M)\beta - (VW/M)\alpha](dt_2/d\theta)$$

$$+ [M + W - (W^2/M)\beta + (W^2/M) + (W^2/M)\alpha\beta - (W^2/M)\alpha - W\alpha\beta]t_2 =$$

$$Mt_o + [(W^2/M)\alpha\beta - W\alpha\beta - (W^2/M)\alpha + (W^2/M) - (W^2/M)\beta + W]T_1 \qquad \text{(A.2.13)}$$

$$F = M + W - (W^2/M)\beta + (W^2/M) + (W^2/M)\alpha\beta - (W^2/M)\alpha - W\alpha\beta$$

$$E = Mt_o + [(W^2/M)\alpha\beta - W\alpha\beta - (W^2/M)\alpha + (W^2/M) - (W^2/M)\beta + W]T_1$$

Auxjliary equation

$$(d^2t_2/d\theta^2) + [2(W/V) + W(M/V) - (W/V)\beta - (W/V)\alpha](dt_2/d\theta)$$

$$+ [(M^2/V^2) + (MW/V^2) - (W^2/V^2)\beta + (W^2/V^2) - (W^2/V^2)\alpha\beta$$

$$- (W^2/V^2)\alpha - (WV/V^2)\alpha\beta]t_2 = 0$$

if,

$$BP = 2(W/V) + (2M/V) - (W/V)\beta - (W/V)\alpha$$

$$DP = (M^2/V^2) + (MW/V^2) - (W^2/V^2)\beta + (W^2/V^2) - (W^2/V^2)\alpha\beta$$
$$- (W^2/V^2)\alpha - (WM/V^2)\alpha\beta$$

Then above equation can be written as

$$m^2 + BPm + DP = 0 \qquad \text{(A.2.14)}$$

The roots of Equation (A.2.14) are

$$m_{1,2} = \frac{-BP \pm \sqrt{BP^2 - 4DP}}{2}$$

and therefore the complementary function is

$$t_{2c} = Ae^{m_1\theta} + Be^{m_2\theta}$$

The right hand side of Equation (A.2.13) is a constant and therefore the particular integral is a constant and equal to the right hand side of Equation (A.2.13) divided by the coefficient t_2, then particular solution is;

$$t_{2p} = E/F = CP \qquad F = DP(V^2/M)$$

And the complete solution is,

$$t_2 = Ae^{m_1\theta} + Be^{m_2\theta} + CP \tag{A.2.15}$$

where A and B arbitrary constants to be calculated from the following initial conditions

at $\theta = 0$ $\quad t_2 = t_{2s}$, $t_1 = t_{1s}$ {After reaching steady-state}

$$CP = \frac{Mt_0 + (W - W\alpha\beta + (W^2/M) - (W^2/M)\alpha - (W^2/M)\beta + (W^2/M)\alpha\beta)T_1}{M + W - W\alpha\beta - (W^2/M)\alpha + (W^2/M)\alpha\beta - (W^2/M)\beta + (W^2/M)}$$

$\theta = 0$ Equation (A.2.15)

$$t_{2s} = A + B + CP$$

$$A = t_{2s} - B - CP$$

Substituting Equation (A.2.15) to Equation (A.2.11)

$$t_1 = (V/M)(m_1 Ae^{m_1\theta} + m_2 Be^{m_2\theta}) + [(W/M)(1 - \beta) + 1](Ae^{m_1\theta} + Be^{m_2\theta} + CP)$$

$$+ ((W/M)\beta - (W/M)T_1 \qquad \text{(A.2.16)}$$

$$\theta = 0 \quad \rightarrow \quad t_1 = t_{1s}$$

$$t_{1s} = (V/M)(m_1 A + m_2 B) + [(W/M)(1 - \beta) + 1](A + B + CP)$$

$$+ ((W/M)\beta - (W/M))T_1$$

$$t_{1s} = (V/M)[m_1(t_{2s} - B - CP) + m_2 B] + [(W/M)(1 - \beta) + 1]t_{2s}$$

$$+ ((W/M)\beta - (W/M))T_1$$

$$t_{1s} = (V/M)(m_1 t_{2s} - mB + m_2 B - m_1 CP) + [(W/M)(1 - \beta) + 1]t_{2s}$$

$$+ ((W/M)\beta - (W/M))T_1$$

$$t_{1s} = ((W/M)\beta - (W/M))T_1 + ((W/M)(1 - \beta) + 1 + (V/M)m_1)t_{2s}$$

$$+ (V/M)(m_2 - m_1)B - (V/M)m_1 CP$$

$$B = \frac{t_{1s} + ((W/M)-(W/M)\beta)T_1 - (V/M)m_1 CP - [(W/M)(1-\beta) + (V/M)m_1 + 1]t_{2s}}{(V/M)(m_2 - m_1)}$$

Using Equations (A.2.7), (A.2.8) and (A.2.15), (A.2.16) and substituting $M = MC_w\rho_w$, $W = WC_h\rho_h$ and $V = VC_w\rho_w$ unknown temperatures are calculated.

APPENDIX III

PROGRAM LISTING

```
      PROGRAM HEAT(DATA,RESULT,TAPE5=DATA,TAPE6=RESULT)
C
C     DETERMINATION OF HEAT TRANSFER COEFFICIENT
C                    FOR SINGLE TANK
C
C     THI THE INLET TEMPERATURE OF HOT STREAM TO TANK   (C)
C     TH2 THE EXIT TEMPERATURE OF HOT STREAM FROM TANK  (C)
C     TCO THE INLET TEMPERATURE OF COLD STREAM TO TANK  (C)
C     TCI THE EXIT TEMPERATURE OF COLD STREAM FROM TANK (C)
C     M  FLOW RATE OF COLD STREAM       (M**3/SEC)
C     W  FLOW RATE OF COLD STREAM       (M**3/SEC)
C     DT DIAMETER OF TANK               (M)
C     DC DIAMETER OF COIL               (M)
C     DH DIAMETER OF TUBE               (M)
C     DA DIAMETER OF AGITATOR           (M)
C     N  AGITATOR SPEED                 (REV/SEC)
C     X  THICKNESS OF TUBE              (M)
C     L  LENGTH OF TUBE                 (M)
C     K  THERMAL CONDUCTIVITY OF TUBE MATERIAL (W/C*M)
C     VH VELOCITY OF HOT STREAM         (M/SEC)
C     CP HEAT CAPACITY                  (J/KG*C)
C     RO DENSITY                        (KG/M**3)
C     MU VISCOSITY                      (KG/M*SEC)
C     V  VOLUMEOF LIQUID IN EACH TANK (M**3)
C     J=1 INDICATES STEADY-STATE CASE
C     J=2 INDICATES UNSTEADY-STATE CASE
C     ICOUNT INDICATES STEPS FOR STEADY-STATE CASE
C     KL     INDICATES STEPS FOR UNSTEADY-STATE CASE
C
C
      DIMENSION THETA(2),TH1(2),TCO(2)
      REAL MUH,MUC,KH,KC,NREH,NPRH,NUDH,NUDC,L,M,MI,M1,M2,N,K,MUW
C
      READ(5,*)DC,DH,DT,L,DA,N,X,K,V,W,M,TCO(1),TH1(1),TCO(2),TH1(2)
      WRITE(6,8) DC,DH,DT,L,DA,N,X,V,W,M,TCO(1),TH1(1),TCO(2),TH1(2)
    8 FORMAT(20X,'DC    =',F7.4,6X,'(M)',/,20X,'DH    =',E11.4,2X,'(M)',/
     +,20X,'DT    =',F7.4,6X,'(M)',/,20X,'L     =',F7.4,6X,'(M)',/,20X,'DA    ='
     +E11.4,2X,'(M)',/,20X,'N     =',F7.4,5X,'(REV/SEC)',/,20X,'X     =',
     +F7.4,6X,'(M)',/,20X,'V     =',E11.4,2X,'(M**3)',/,20X,'W     =',F11.4,
     +2X,'(M**3/SEC)',/,20X,'M     =',E11.4,2X,'(M**3/SEC)',/,20X,'TCO(1)='
     +,F5.2,6X,'(C)',/,20X,'TH1(1)=',F5.2,6X,'(C)',/,20X,'TCO(2)=',F5.2,
     +6X,'(C)',/,20X,'TH1(2)=',F5.2,6X,'(C)',//)
C
C
      THETA(1)=50000.
      THETA(2)=0.
      ICOUNT=0
      A=1.
C
C     STEADY-STATE CASE
C
C
      J=1
      VH=W/((3.1416*DH*DH)/4.)
      ROC=FRO(TCO(J))
      ROH=FRO(TH1(J))
      MUC=FMU(TCO(J))
      MUH=FMU(TH1(J))
      CPC=FCP(TCO(J))
      CPH=FCP(TH1(J))
      KC =FK (TCO(J))
      KH =FK (TH1(J))
      MUW=1.
      NUC=1.
      NUH=1.
      IF(ICOUNT.EQ.0)GO TO 66
```

```
   11 THO=(TH2+TH1(J))/2.
      IF(J.GT.1) GO TO 33
      X1=TC1
      X2=TH2
C
   33 ROC=FRO(TC1)
      ROH=FRO(THO)
      MUC=FMU(TC1)
      MUH=FMU(THO)
      CPC=FCP(TC1)
      CPH=FCP(THO)
      KC =FK (TC1)
      KH =FK(THO)
      IF(ICOUNT.EQ.1) GO TO 66
      MUW=FMU(TW)
   66 NREH=(DH*(W/((3.1416*DH*DH)/4.))*ROH)/MUH
      NPRH=(CPH*MUH)/KH
C LAMINAR FLOW
      IF(NREH.GT.100)GO TO 83
      NUDH=1.86*((NREH*NPRH)/(L/DH))**0.33
      HI=(KH*NUDH)/DH
      GO TO 55
C
C TRANSITION REGION
   77 IF (NREH.GT.10000) GO TO 83
      E=0.116*((NREH)**0.67-125.)/NREH
      X=(3.1416*ROH*VH*CPH*DH*DH)/(4.*KH*L)
      HI=1.75*KH/DH*((3.1416*DH)/(4.*L)*NREH*NPRH)**.33
      GO TO 55
C
C TURBULENT FLOW
   83 NUDH=0.023*NREH**0.8*NPRH**0.33*(MUH/MUW)**0.14
      HI=((KH*NUDH)/DH)*(1+3.5*DH/DC)
   55 HO=(KC/DT)*1.40*((((DA**2)*N*ROC)/MUC)**0.62
     +*((CPC*MUC)/KC)**0.33*(MUC/MUW)**0.14
      IF(ICOUNT.EQ.0) GO TO 56
      DELT=(THO-TC1)/(1.+(HI/HO))
      TW=THO-DELT
   56 U=1./(1./HI+1./HO+2.6E-5)
      ALPHA=EXP(-U*(3.1416*DH*L)/(W*ROH*CPH))
C
      VI=V*ROC
      WI=W*ROH
      MI=M*ROC
      G=VI*CPC
      F=MI*CPC+WI*CPH*(1.-ALPHA)
      H=WI*CPH*(1.-ALPHA)*TH1(J)+MI*CPC*TCO(J)
      B=H/F
      IF(ICOUNT.EQ.0) GO TO 21
      TC1S=TC1
      A=TC1S-B
   21 TC1=A*EXP(-(F/G)*THETA(J))+B
      TH2=ALPHA*TH1(J)+(1.-ALPHA)*TC1
      IF(J.EQ.1)GO TO 7
      WRITE(6,1) THETA(2),TC1,TH2
    1 FORMAT(7X,F7.2,10X,F6.3,10X,F6.3)
      GO TO 101
    7 IF(ICOUNT.EQ.0) GO TO 3
      DIFR1=X1-TC1
      DIFR2=X2-TH2
      IF(DIFR1.GT.0.0001) GO TO 3
      IF(DIFR2.GT.0.0001) GO TO 3
      IF(A.NE.0)GO TO 3
      WRITE(6,6) TC1,TH2
    6 FORMAT(10X,'TC1S=',F6.3,5X,'TH2S=',F6.3)
      GO TO 99
```

```
    3   ICOUNT=ICOUNT +1
        GO TO 11
   99   WRITE(6,2)
    2   FORMAT(10X,'TIME',10X,'TCOLD1',10X,'THOT2',
+       /,10X,4('_'),10X,6('_'),10X,5('_'))
C
C       UNSTEADY-STATE CASE
C
        J=2
        KL=0.
  101   THETA(J)=THETA(J)+30.
        IF(THETA(J).GT.1800) GO TO 111
        KL=KL+1
        IF(KL.GT.1) GO TO 21
        GO TO 11
  111   STOP
        END
        FUNCTION FCP(T)
        FCP=.419313E+4-.744678*T+.100875E-1*T*T
        RETURN
        END
        FUNCTION FMU(T)
        FMU=.148237E-2-.295743E-4*T+.258156E-6*T*T-.822939E-9*T*T*T
        RETURN
        END
        FUNCTION FRO(T)
        FRO=1./(.997426E-3+.135802E-6*T+.325184E-8*T*T)
        RETURN
        END
        FUNCTION FK(T)
        FK=.570671+.178690E-2*T-.684359E-5*T*T
        RETURN
        END
10.35.23.UCLP, AA, P04     ,       0.199KLNS.
```

```
      PROGRAM HEAT(DATA,RESULT,TAPE5=DATA,TAPE6=RESULT)
C
C      DETERMINATION OF HEAT TRANSFER COEFFICIENT
C            FOR TWO TANKS IN SERIES
C
C      THI THE INLET TEMPERATURE OF HOT STREAM TO TANK 2(C)
C      TH2 THE EXIT TEMPERATURE OF HOT STREAM FROM TANK 2(C)
C      TH3 THE EXIT TEMPERATURE OF HOT STREAM FROM TANK 1(C)
C      TCO THE INLET TEMPERATURE OF COLD STREAM TO TANK 1(C)
C      TC1 THE EXIT TEMPERATURE OF COLD STREAM FROM TANK1(C)
C      TC2 THE EXIT TEMPERATURE OF COLD STREAM FROM TANK 2(C)
C     M   FLOW RATE OF COLD STREAM       (M**3/SEC)
C     W   FLOW RATE OF COLD STREAM       (M**3/SEC)
C     DT DIAMETER OF TANK                (M)
C     DC DIAMETER OF COIL                (M)
C     DH DIAMETER OF TUBE                (M)
C     DA DIAMETER OF AGITATOR            (M)
C     N   AGITATOR SPEED                 (REV/SEC)
C     X   THICKNESS OF TUBE              (M)
C     L   LENGTH OF TUBE                 (M)
C     K   THERMAL CONDUCTIVITY OF TUBE MATARIAL (W/C*M)
C     VH VELOCITY OF HOT STREAM          (M/SEC)
C     CP HEAT CAPACITY                   (J/KG*C)
C     RO DENSITY                         (KG/M**3)
C     MU VISCOSITY                       (KG/M*SEC)
C     V   VOLUME OF LIQUID IN EACH TANK (M**3)
C     J=1 INDICATES STEADY-STATE CASE
C     J=2 INDICATES UNSTEADY-STATE CASE
C     I    INDICATES TANK NUMBER
C     ICOUNT  INDICATES  STEPS FOR STEADY-STATE CASE
C     KL        INDICATES  STEPS FOR UNSTEADY-STATE CASE
C
C
      DIMENSION ROC(2),ROH(2),MUC(2),MUH(2),THO(2),TC(2),
     + KC(2),KH(2),NREH(2),NPRH(2),NUDH(2),NUDC(2),HI(2),
     + HO(2),U(2),CPC(2),CPH(2),MUW(2),THETA(2),TH1(2),
     + TCO(2),DELT(2),TW(2)
      REAL MUH,MUC,KH,KC,NREH,NPRH,NUDH,NUDC,L,M,MI,M1,M2,N,K,MUW
C
C
      READ(5,*)DC,DH,DT,L,DA,N,X,K,V,W,M,TCO(1),TH1(1),TCO(2),TH1(2)
      WRITE(6,3) DC,DH,DT,L,DA,N,X,V,W,M,TCO(1),TH1(1),TCO(2),TH1(2)
    3 FORMAT(20X,'DC   =',F7.4,6X,'(M)',/,20X,'DH   =',E11.4,2X,'(M)',/
     + ,20X,'DT   =',F7.4,6X,'(M)',/,20X,'L    =',F7.4,6X,'(M)',/20X,'DA   =',
     + E11.4,2X,'(M)',/,20X,'N    =',F7.4,6X,'(REV/SEC)',/,20X,'X    =',
     + F7.4,6X,'(M)',/,20X,'V    =',E11.4,2X,'(M**3)',/,20X,'W    =',E11.4,
     + 2X,'(M**3/SEC)',/,20X,'M    =',E11.4,2X,'(M**3/SEC)',/,20X,'TCO(1)='
     + ,F5.2,6X,'(C)',/,20X,'TH1(1)=',F5.2,6X,'(C)',/,20X,'TCO(2)=',F5.2,
     + 6X,'(C)',/,20X,'TH1(2)=',F5.2,6X,'(C)',//)
C
C
      THETA(1)=10000.
      THETA(2)=0.
      A=1.
      B=1.
      I=1
      ICOUNT=0
C
C     STEADY-STATE CASE
C
      J=1
      VH=W/((3.1416*DH*DH)/4.)
      ROC(1)=FRO(TCO(J))
      ROH(1)=FRO(TH1(J))
      MUC(1)=FMU(TCO(J))
      MUH(1)=FMU(TH1(J))
```

```
0740      CPC(1)=FCP(TCO(J))
      CPH(1)=FCP(TH1(J))
      KC (1) =FK(TCO(J))
      KH (1)=FK (TH1(J))
      CC=CPC(1)
      CH=CPH(1)
      RC=ROC(1)
      RH=ROH(1)
      MUW(1)=1.
      MUH(1)=1.
      MUC(1)=1.
      MUW(2)=1.
      NI=N
      WI=W
      VI=V
C
      IF(ICOUNT.EQ.0)GO TO 66
   11 I=1
      THO(1)=(TH3+TH2)/2.
      THO(2)=(TH2+TH1(J))/2.
      TC(1)=TC1
      TC(2)=TC2
      IF(J.GT.1) GO TO 33
      X1=TC2
      X2=TC1
      X3=TH2
      X4=TH3
C
   33 ROC(I)=FRO(TC(I))
      ROH(I)=FRO(THO(I))
      MUC(I)=FMU(TC(I))
      MUH(I)=FMU(THO(I))
      CPC(I)=FCP(TC(I))
      CPH(I)=FCP(THO(I))
      KC (I)=FK (TC(I))
      KH (I)=FK(THO(I))
      IF(ICOUNT.EQ.1) GO TO 66
      MUW(I)=FMU(TW(I))
   66 NREH(I)=(DH*(W/((3.1416*DH*DH)/4.))*ROH(I))/MUH(I)
      NPRH(I)=(CPH(I)*MUH(I))/KH(I)
C  LAMINAR FLOW
      IF(NREH(I).GT.100)GO TO 77
      NUDH(I)=1.86*((NREH(I)*NPRH(I))/(L/DH))**0.33
      HI(I)=(KH(I)*NUDH(I))/DH
      GO TO 55
C
C  TRANSITION REGION
   77 IF (NREH(I).GT.10000) GO TO 88
      B=0.116*((NREH(I))**0.67-125.)/NREH(I)
      X=(3.1416*ROH(I)*VH*CPH(I)*DH*DH)/(4.*KH(I)*L)
      HI(I)=1.75*KH(I)/DH*((3.1416*DH)/(4.*L)*NREH(I)*NPRH(I))**.33
      GO TO 55
C
C  TURBULENT FLOW
   88 NUDH(I)=0.023*NREH(I)**0.8*NPRH(I)**0.33
      HI(I)=((KH(I)*NUDH(I))/DH)*(1+3.5*DH/DC)*(MUH(I)/MUW(I))**0.14
   55 HO(I)=((KC(I)/DT)*1.40*(((DA**2)*N*ROC(I))/MUC(I))**0.52
     + *((CPC(I)*MUC(I))/KC(I))**0.33*(MUC(I)/MUW(I))**0.14
      IF(ICOUNT.EQ.0) GO TO 56
      DELT(I)=(THO(I)-TC(I))/(1.+(HI(I)/HO(I)))
      TW(I)=THO(I)-DELT(I)
   56 U(I)=1./(1./HI(I)+1./HO(I)+2.6E-5)
      IF (ICOUNT.EQ.0) GO TO 43
      I=I+1
      IF(I.GT.2) GO TO 44
      GO TO 33
```

```
 43   U(2)=U(1)
      CPH(2)=CPH(1)
      ROH(2)=ROH(1)
 44   ALPHA=EXP(-U(1)*(3.1416*DH*L)/(W*ROH(1)*CPH(1)))
      BETA=EXP(-U(2)*(3.1416*DH*L)/(W*ROH(2)*CPH(2)))
C
      IF(ICOUNT.EQ.0) GO TO 72
C
 22   TCL=(TC1+TC2)/2.
      THL=(TH1(J)+TH3)/2.
      CC=FCP(TCL)
      CH=FCP(THL)
      RC=FRO(TCL)
      RH=FRO(THL)
      MI=W*CC*RC
      WI=W*CH*RH
      VI=V*CC*RC
 72   BP=2.*(MI/VI)+(WI/VI)*(2.-BETA-ALPHA)
      DP=(MI*MI)/(VI*VI)+((MI*WI)/(VI*VI))*(1-ALPHA*BETA)+
     +  ((WI*WI)/(VI*VI))*(1+ALPHA*BETA-ALPHA-BETA)
      M1=(-BP+((BP*BP)-(4*DP))**0.5)/2.
      M2=(-BP-((BP*BP)-(4*DP))**0.5)/2.
      CP=(MI*TCO(J)+TH1(J)*(WI-WI*ALPHA*BETA+((WI*WI)/MI)
     +  *(1-ALPHA-BETA+ALPHA*BETA)))/(MI+WI-WI*ALPHA*BETA+
     +  ((WI*WI)/MI)*(1-ALPHA-BETA+ALPHA*BETA))
      IF(ICOUNT.EQ.0) GO TO 21
      TC1S=TC1
      TC2S=TC2
      K=(WI/MI)*(BETA-1.)
      B1=TC1S-K*TH1(J)-(1-K)*TC2S+(VI/MI)*M1*(CP-TC2S)
      B2=(VI/MI)*(M2-M1)
      B=B1/B2
      A=TC2S-B-CP
 21   TC2=A*EXP(M1*THETA(J))+B*EXP(M2*THETA(J))+CP
      TC1=(VI/MI)*(M1*A*EXP(M1*THETA(J))+M2*B*EXP(M2*THETA(J)))
     +  +TC2+(WI/MI)*(1-BETA)*(TC2-TH1(J))
      TH2=BETA*TH1(J)+(1-BETA)*TC2
      TH3=ALPHA*TH2+(1-ALPHA)*TC1
      IF(J.EQ.1)GO TO 7
      WRITE(6,1) THETA(2),TC1,TC2,TH2,TH3
  1   FORMAT(7X,F7.2,10X,F6.3,10X,F6.3,2(9X,F6.3))
      GO TO 101
  7   IF(ICOUNT.EQ.0) GO TO 3
      DIFR1=X1-TC2
      DIFR2=X2-TC1
      DIFR3=X3-TH2
      DIFR4=X4-TH3
      IF(DIFR1.GT.0.0001) GO TO 3
      IF(DIFR2.GT.0.0001) GO TO 3
      IF(DIFR3.GT.0.0001) GO TO 3
      IF(DIFR4.GT.0.0001) GO TO 3
      WRITE(6,5) TC1,TC2,TH2,TH3
  5   FORMAT(10X,'TC1S=',F6.3,5X,'TC2S=',F6.3,5X,'TH2S=',F6.3,
     +  5X,'TH3S=',F6.3)
      GO TO 99
  3   ICOUNT=ICOUNT +1
      GO TO 11
 99   WRITE(6,2)
  2   FORMAT(10X,'TIME',10X,'TCOLD1',10X,'TCOLD2',10X,'THOT2',
     +  10X,'THOT3',/,10X,4('_'),10X,6('_'),10X,6('_'),10X,5('_'),
     +  10X,5('_'))
C
C      UNSTEADY-STATE CASE
C
      J=2
      KL=0.
```

```
 101  THETA(J)=THETA(J)+30.
      IF(THETA(J).GT.2400) GO TO 111
      KL=KL+1
      IF(KL.GT.1) GO TO 21
      GO TO 11
 111  STOP
      END
      FUNCTION FCP(T)
      FCP=.419315E+4-.744673*T+.100875E-1*T**2.
      RETURN
      END
      FUNCTION FMU(T)
      FMU=.148237E-2-.295743E-4*T+.258156E-6*T*T-.322939E-9*T*T*T
      RETURN
      END
      FUNCTION FRO(T)
      FRO=1./(.997426E-3+.135802E-6*T+.325184E-8*T*T)
      RETURN
      END
      FUNCTION FK(T)
      FK=.573571+.178690E-2*T-.684359E-5*T*T
      RETURN
      END
09.51.49.UCLP, AA, P04     ,       0.255KLNS.
```

APPENDIX IV

PHYSICAL PROPERTIES OF WATER

In this section physical properties of water as a function of temperature are given [35].

A.4.A FUNCTION FK(T)

FK(T) subprogram, using following equation

$$K = 0.570671 + 0.178690\text{x}10^{-2}T - 0.684359\text{x}10^{-5}T^2$$

calculates thermal conductivity of water at a given temperature.

A.4.B FUNCTION FMU(T)

FMU(T) subprogram calculates viscosity of water at a given temperature, using equation given below.

$$\mu = 0.148237\text{x}10^{-2} - 0.295743\text{x}10^{-4}T + 0.258156\text{x}10^{-6}T^2 - 0.822939\text{x}10^{-9}T^3$$

A.4.C FUNCTION FCP(T)

FCP(T) subprogram calculates specific heat of water at a given temperature, using following equation.

$$CP = 0.419318\text{x}10^{4} - 0.744678T + 0.100875\text{x}10^{-1}T^2$$

A.4.D FUNCTION FRO(T)

FRO(T) subprogram calculates density of water at a given temperature, using following equation

$$\rho = 1/(0.997426\text{x}10^{-3} + 0.135802\text{x}10^{-6}T + 0.325184\text{x}10^{-8}T^{2})$$

APPENDIX V

DERIVATION OF ERROR EQUATIONS

Empirical equation used to calculate film heat transfer coefficient in agitated side of vessel is,

$$HO = 1.40(D_T^{-1})k(D_A^2N\rho/\mu)^{0.62}(C_p\mu/k)^{1/3}(\mu/\mu_w)^{0.14}$$

where

$$\rho = f(T), \quad \mu = f(T), \quad C_p = f(T), \quad \mu_w = w(T_w)$$

and

$$HO = f(D_T, D_A, N, T, T_w)$$

$$HO = 1.40D_T^{-1}D_A^{1.24}N^{0.62}k^{0.77}\rho^{0.62}C_p^{0.33}\mu^{-0.15}\mu_w^{-0.14} \qquad (A.5.1)$$

Taking the partial derivatives of Eq. (A.5.1)

$$dHO = \frac{\partial f}{\partial D_T}\,dD_T + \frac{\partial f}{\partial D_A}\,dD_A + \frac{\partial f}{\partial N}\,dN + \frac{\partial f}{\partial T}\,dT + \frac{\partial f}{\partial T_w}\,dT_w \qquad (A.5.2)$$

$$\frac{\partial f}{\partial D_C} = 1.40[-D_T^{-2}]k^{0.77}D_A^{1.24}\ N^{0.62}\rho^{0.62}C_p^{0.33}\ \mu_w^{-0.14}\mu^{-0.15}$$

$$\frac{\partial f}{\partial D_A} \doteq 1.40[1.24D_A^{0.24}]D_T^{-1}N^{0.62}k^{0.77}\rho^{0.62}C_p^{0.33}\mu_w^{-0.14}\mu^{-0.15}$$

$$\frac{\partial f}{\partial N} = 1.40[0.62N^{-0.38}]D_T^{-1}D_A^{1.24}N^{0.62}k^{0.77}\rho^{0.62}C_p^{0.33}\mu_w^{-0.14}\mu^{-0.15}$$

$$\frac{\partial f}{\partial T_w} = 1.40[-0.14(\mu_w)'\mu_w^{-1.14}]D_T^{-1}D_A^{1.24}N^{0.62}k^{0.77}\rho^{0.62}C_p^{0.33}\mu_w^{-0.14}\mu^{-0.15}$$

$$\frac{\partial f}{\partial T} = 1.40[0.77(k)'k^{-0.33}\rho^{0.62}C_p^{0.33}\mu^{-0.15} + 0.62(\rho)'\rho^{-0.38}k^{0.77}$$

$$\cdot C_p^{0.33}\mu^{-0.15} + 0.33(C_p)'C_p^{-0.77}k^{0.33}\rho^{0.62}\mu^{-0.15}$$

$$- 0.15(\mu)'\mu^{-1.15}k^{0.77}\rho^{0.77}C_p^{0.33}]D_T^{-1}D_A^{1.24}N^{0.62}$$

where,

$(\mu_w)'$, $(\mu)'$, $(k)'$, $(C_p)'$, $(\rho)'$ are derivative values.

Provided the errors δHO, δD_C, δD_A, δN, δT and δT_w are small, dHO, dD_c, dD_A, dN, dT, dT_w can be replaced by them in Equation (A.5.2). Thus

$$\delta HO = 1.40D_T^{-1}D_A^{1.24}N^{0.62}k^{0.77}C_p^{0.33}\rho^{0.62}\mu_w^{-0.14}\mu^{-0.15}[-(\delta D_T/D_T)$$

$$+ 1.24(\delta D_A/D_A) + 0.62(\delta N/N) - 0.14(\mu_w)'(\delta T_w/\mu_w)$$

$$+ (0.77((k)'/k) + 0.62((\rho)'/\rho) + 0.33((C_p)'/C_p)$$

$$- 0.15((\mu)'/\mu)\delta T]$$

finally;

$$\delta HO/HO = |-\delta D_T/D_T| + |1.24\delta D_A/D_A| + |0.62\delta N/N| + |-0.14(\mu_w)'(\delta T_w/\mu_w)|$$

$$+ |0.77(k)'(\delta T/k)| + |0.62(\rho)'(\delta T/\rho)| + |0.33(C_p)'(\delta T/C_p)|$$

$$+ |-0.15(\mu)'(\delta T/\mu)|$$

is found. Knowing the all other variables HO and so, unknown true value of HO' can be calculated.

Empirical equation used to calculate film heat transfer coefficient in the coil side is;

$$HI = 0.023k\ D_H^{-1}(C_p\mu/k)^{0.33}(D_H V_H/\mu)^{0.8}(\mu/\mu_w)^{0.14}(1 + 3.5(D_H/D_c))$$

$$V_H = \frac{W}{(3.1416/4)D_H^2}$$

$$HI = 0.028k^{0.77}\mu^{-0.33}C_p^{0.33}\ \mu_w^{-0.14}D_H^{-1.8}W^{0.8}$$

$$+ 0.098k^{0.77}\mu^{-0.33}C_p^{0.33}\mu_w^{-0.14}W^{0.8}D_c^{-1}D_H^{-0.8} \qquad \text{(A.5.3)}$$

It can be shown that

$$HI = f_1(D_H, W, T, T_w) + f_2(W, D_H, D_c, T, T_w)$$

Taking the partial derivative of Equation (A.5.3)

$$dHI = (\partial f_1/\partial D_H)dD_H + (\partial f_1/\partial W)dW + (\partial f_1/\partial T_w)dT_w + (\partial f_1/\partial T)dT$$

$$+ (\partial f_2/\partial D_H) + (\partial f_2/\partial W)dW + (\partial f_2/\partial D_c)dD_c + (\partial f_2/\partial T_w)dT_w$$

$$+ (\partial f_2/\partial T)dT \qquad \text{(A.5.4)}$$

$$\frac{\partial f_1}{\partial D_H} = 0.028[-1.8D_H^{-2.8}]k^{0.77}\mu^{-0.33}C_p^{0.33}\mu_w^{-0.14}W^{0.8}$$

$$\frac{\partial f_1}{\partial V_H} = 0.023[0.8W^{0.2}]k^{0.77}\mu^{-0.33}C_p^{0.33}\mu_w^{-0.14}D_H^{-1.8}$$

$$\frac{\partial f_1}{\partial T_w} = 0.023[-0.14(\mu_w)'\mu_w^{-1.14}]k^{0.77}\mu^{-0.33}C_p^{0.33}\ D_H^{-1.8}W^{0.8}$$

$$\frac{\partial f_1}{\partial T} = 0.023[(0.77(k)'k^{-0.33}\mu^{-0.33}C_p^{0.33} - 0.33(\mu)'\mu^{-1.33}k^{0.77}C_p^{0.33}$$

$$+ 0.33(C_p)'C_p^{-0.77}k^{0.77}\mu^{-0.33}]D_H^{-1.8}W^{0.8}\mu_w^{-0.14}$$

$$\frac{\partial f_2}{\partial D_H} = 0.098[-0.8D_H^{-1.8}]k^{0.77}\mu^{-0.33}C_p^{0.33}\mu_w^{-0.14}W^{0.8}D_c^{-1}$$

$$\frac{\partial f_2}{\partial D_c} = 0.098[-D_c^{-2}]k^{0.77}\mu^{-0.33}C_p^{0.33}\mu_w^{-0.14}W^{0.8}D_H^{-0.8}$$

$$\frac{\partial f_2}{\partial W} = 0.098[0.8W^{-0.2}]k^{0.77}\mu^{-0.33}C_p^{0.33}\mu_w^{-0.14}D_c^{-1}D_H^{-0.8}$$

$$\frac{\partial f_2}{\partial T_w} = 0.098[-0.14(\mu_w)'\mu_w^{-1.14}]k^{0.77}\mu^{-0.33}C_p^{0.33}W^{0.8}D_c^{-1}D_H^{-0.8}$$

$$\frac{\partial f_2}{\partial T} = 0.098[0.77(k)'k^{-0.33}\mu^{-0.33}C_p^{0.33} - 0.33(\mu)'\mu^{-1.33}k^{0.77}C_p^{0.33}$$

$$+ 0.33(C_p)'C_p^{-0.77}k^{0\div 77}\mu^{-0.33}]D_H^{-0.8}D_c^{-1}W^{0.8}\mu_w^{-0.14}$$

Provided the errors δHI, δD_c, δD_H, δW, δT, δT_w are small enough dHI, dD_c, dD_H, dW, dT, dT_w can be replaced by them in Equation (A.5.4). Thus

$$\delta HI = 0.028k^{0.77}\mu^{-0.33}C_p^{0.33}\mu_w^{-0.14}W^{0.8}D_H^{-1.8}[-1.8(\delta D_H/D_H)$$

$$+ 0.8(\delta W/W) - 0.14(\delta_w)'(\delta T_w/\mu_w) + (0.77((k)'/k)$$

$$- 0.33((\mu)'/\mu) + 0.33((C_p)'/C_p))\delta T$$

$$+ 0.098k^{0.77}\mu^{-0.33}C_p^{0.33}\mu_w^{-0.14}D_H^{-0.8}W^{0.8}D_c^{-1}[0.8(\delta W/W)$$

$$- (\delta D_c/D_c) - 0.8(\delta D_H/D_H) - 0.14(\mu_w)'(\delta T_w/\mu_w)$$

$$+ 0.77(k)'(\delta T/k) - 0.33(\mu)'(\delta T/\mu)] + 0.33((C_p)'/C_p)\delta T$$

and final form of the equation is,

$$\delta HI = HI[|-0.8(\delta D_H/D_H)| + |0.8(\delta W/W)| + |-0.14((\mu_w)'/\mu_w)(\delta T_w)|$$

$$+ |0.77((k)'/k) + 0.33((C_p)'/C_p) - 0.33((\mu)'/\mu)|\delta T]$$

$$+ |0.028k^{0.77}C_p^{0.33}\mu^{-0.33}\mu_w^{-0.14}W^{0.8}D_H^{-1.8}(-\delta D_H/D_H)$$

$$+ 0.098k^{0.77}C_p^{0.33}\mu^{-0.33}\mu_w^{-0.14}W^{0.8}D_H^{-0.8}D_c^{-1}(-\delta D_c/D_c)|$$