LOCAL HEAT TRANSFER IN A MIXING
VESSEL USING HEAT FLUX SENSORS

A THESIS

Presented in Partial Fulfillment of the Requirements for
the degree Master of Science in the
Graduate School of the Ohio State University

by

Seungjoo Haam, B. S.

* * * * *

The Ohio State University

1990

Master's Examination Committee:

R. S. Brodkey

Jacques L. Zakin

Approved by

A handwritten signature in black ink, appearing to read "Robert S. Brodkey", written over a horizontal line.

Adviser

Department of
Chemical Engineering

ACKNOWLEDGEMENTS

I thank Professor Robert S. Brodkey with deepest gratitude for his guidance, encouragement, and support through the course of this research project. I gratefully acknowledge the financial support provided by Chemineer, Inc. and the guidance from Dr. Julian Fasano. Thanks to Dr. Jacques L. Zakin for his comments and review of this manuscript. The assistance from Mike Kukla and Keith Russ is gratefully appreciated. Specially, I would like to thank my parents and families for their support and love.

VITA

December 2, 1965 Born - Seoul, Korea

1988 B. S., Yonsei University in
Seoul, Korea

1988 - Present Research Associate
Chemical Engineering Department
The Ohio State University
Columbus, Ohio

FIELDS OF STUDY

Major Field: Chemical Engineering

Studies in: Fluid Mechanics, Robert S. Brodkey

TABLE OF CONTENTS

ACKNOWLEDGEMENTS	ii
VITA	iii
TABLE OF CONTENTS	iv
LIST OF FIGURES	vi
LIST OF TABLES	xiii
LIST OF PLATES	xiv

CHAPTER	PAGES
I. INTRODUCTION	1
II. LITERATURE REVIEW	2
2.1 Dimensional Analysis	2
2.1.1 Navier-Stokes Equation	2
2.1.2 Dimensionless Numbers	4
2.1.2.1 Reynolds Number	4
2.1.2.2 Power Number	4
2.1.2.3 Froude Number	9
2.1.2.4 Blend Number	9
2.1.2.5 Pumping Number	9
2.1.2.6 Weber Number	9
2.2 Heat Transfer in the Agitated System	10
2.2.1 Heat Transfer	10
2.2.2 Dimensional Analysis for Heat Transfer Coefficient ..	10
2.2.3 Correlations for Heat Transfer	11
III. EXPERIMENTAL	13
3.1 Experimental Equipments	13
3.1.1 Agitated Vessel	13
3.1.2 Mixing Drive	15
3.1.3 Input Digital Tachometer	15
3.1.4 Impellers	17
3.1.5 Heat Flux Sensor and Thermocouple	17
3.1.6 Data Acquisition System	23
3.2 Data Acquisition Programs	24
3.2.1 Raw Data	24

3.2.2	Conversion	24
3.3	Experimental Procedure	25
IV.	RESULTS	28
4.1	Preliminary Observations	28
4.2	Introduction to Detail Measurements	70
4.3	Rushton D-6 Impeller	70
4.4	P-4 Impeller	77
4.5	HE-3 Impeller	85
V.	DISCUSSION	92
	REFERENCES	120
Appendix A.	Program List for Obtaining the Raw Data	122
Appendix B.	Program List for Conversion	133

LIST OF FIGURES

FIGURE	PAGE
1. Power Number (from ref. [7])	7
2. Power Requirements for Agitated Systems (from ref. [7])	8
3. Experimental Apparatus	14
4. The Dimensions of the Agitated Vessel	16
5. Flow Patterns for Flat-blade - Radial Flow (from Ref. [2]) ...	21
6. Flow Patterns for Pitched-blade - Axial Flow (from Ref. [2]) .	22
7. Incremental Baffle rotation Settings	26
8. Heat Transfer Coefficient at Probe B; D-6 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/3$, $C/T = 1/3$ and $D/T = 1/3$, $C/T = 1/4$	29
9. Heat Transfer Coefficient at Probe B; D-6 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/2$, $C/T = 1/3$ and $D/T = 1/2$, $C/T = 1/4$	30
10. Heat Transfer Coefficient at Probe 1; D-6 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/3$, $C/T = 1/3$ and $D/T = 1/3$, $C/T = 1/4$	31
11. Heat Transfer Coefficient at Probe 1; D-6 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/2$, $C/T = 1/3$ and $D/T = 1/2$, $C/T = 1/4$	32
12. Heat Transfer Coefficient at Probe 2; D-6 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/3$, $C/T = 1/3$ and $D/T = 1/3$, $C/T = 1/4$	33
13. Heat Transfer Coefficient at Probe 2; D-6 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/2$, $C/T = 1/3$ and $D/T = 1/2$, $C/T = 1/4$	34

14.	Heat Transfer Coefficient at Probe B; D-6 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/3$, $C/T = 1/3$ and $D/T = 1/3$, $C/T = 1/4$	35
15.	Heat Transfer Coefficient at Probe B; D-6 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/2$, $C/T = 1/3$ and $D/T = 1/2$, $C/T = 1/4$	36
16.	Heat Transfer Coefficient at Probe 1; D-6 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/3$, $C/T = 1/3$ and $D/T = 1/3$, $C/T = 1/4$	37
17.	Heat Transfer Coefficient at Probe 1; D-6 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/2$, $C/T = 1/3$ and $D/T = 1/2$, $C/T = 1/4$	38
18.	Heat Transfer Coefficient at Probe 2; D-6 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/3$, $C/T = 1/3$ and $D/T = 1/3$, $C/T = 1/4$	39
19.	Heat Transfer Coefficient at Probe 2; D-6 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/2$, $C/T = 1/3$ and $D/T = 1/2$, $C/T = 1/4$	40
20.	Heat Transfer Coefficient at Probe B; D-6 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/3$, $C/T = 1/3$ and $D/T = 1/2$, $C/T = 1/3$	41
21.	Heat Transfer Coefficient at Probe B; D-6 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/3$, $C/T = 1/4$ and $D/T = 1/2$, $C/T = 1/4$	42
22.	Heat Transfer Coefficient at Probe B; D-6 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/3$, $C/T = 1/3$ and $D/T = 1/2$, $C/T = 1/3$	43
23.	Heat Transfer Coefficient at Probe B; D-6 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/3$, $C/T = 1/4$ and $D/T = 1/2$, $C/T = 1/4$	44
24.	Heat Transfer Coefficient at Probe B; P-4 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/3$, $C/T = 1/3$ and $D/T = 1/3$, $C/T = 1/4$	45
25.	Heat Transfer Coefficient at Probe B; P-4 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/2$, $C/T = 1/3$ and $D/T = 1/2$, $C/T = 1/4$	46

26.	Heat Transfer Coefficient at Probe 1; P-4 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/3$, $C/T = 1/3$ and $D/T = 1/3$, $C/T = 1/4$	47
27.	Heat Transfer Coefficient at Probe 1; P-4 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/2$, $C/T = 1/3$ and $D/T = 1/2$, $C/T = 1/4$	48
28.	Heat Transfer Coefficient at Probe 2; P-4 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/3$, $C/T = 1/3$ and $D/T = 1/3$, $C/T = 1/4$	49
29.	Heat Transfer Coefficient at Probe 2; P-4 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/2$, $C/T = 1/3$ and $D/T = 1/2$, $C/T = 1/4$	50
30.	Heat Transfer Coefficient at Probe B; P-4 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/3$, $C/T = 1/3$ and $D/T = 1/3$, $C/T = 1/4$	51
31.	Heat Transfer Coefficient at Probe B; P-4 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/2$, $C/T = 1/3$ and $D/T = 1/2$, $C/T = 1/4$	52
32.	Heat Transfer Coefficient at Probe 1; P-4 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/3$, $C/T = 1/3$ and $D/T = 1/3$, $C/T = 1/4$	53
33.	Heat Transfer Coefficient at Probe 1; P-4 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/2$, $C/T = 1/3$ and $D/T = 1/2$, $C/T = 1/4$	54
34.	Heat Transfer Coefficient at Probe 2; P-4 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/3$, $C/T = 1/3$ and $D/T = 1/3$, $C/T = 1/4$	55
35.	Heat Transfer Coefficient at Probe 2; P-4 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/2$, $C/T = 1/3$ and $D/T = 1/2$, $C/T = 1/4$	56
36.	Heat Transfer Coefficient at Probe B; HE-3 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/3$, $C/T = 1/3$ and $D/T = 1/3$, $C/T = 1/4$	57
37.	Heat Transfer Coefficient at Probe B; HE-3 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/2$, $C/T = 1/3$	

and $D/T = 1/2$, $C/T = 1/4$	58
38. Heat Transfer Coefficient at Probe 1; HE-3 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/3$, $C/T = 1/3$ and $D/T = 1/3$, $C/T = 1/4$	59
39. Heat Transfer Coefficient at Probe 1; HE-3 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/2$, $C/T = 1/3$ and $D/T = 1/2$, $C/T = 1/4$	60
40. Heat Transfer Coefficient at Probe 2; HE-3 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/3$, $C/T = 1/3$ and $D/T = 1/3$, $C/T = 1/4$	61
41. Heat Transfer Coefficient at Probe 2; HE-3 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/2$, $C/T = 1/3$ and $D/T = 1/2$, $C/T = 1/4$	62
42. Heat Transfer Coefficient at Probe B; HE-3 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/3$, $C/T = 1/3$ and $D/T = 1/3$, $C/T = 1/4$	63
43. Heat Transfer Coefficient at Probe B; HE-3 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/2$, $C/T = 1/3$ and $D/T = 1/2$, $C/T = 1/4$	64
44. Heat Transfer Coefficient at Probe 1; HE-3 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/3$, $C/T = 1/3$ and $D/T = 1/3$, $C/T = 1/4$	65
45. Heat Transfer Coefficient at Probe 1; HE-3 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/2$, $C/T = 1/3$ and $D/T = 1/2$, $C/T = 1/4$	66
46. Heat Transfer Coefficient at Probe 2; HE-3 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/3$, $C/T = 1/3$ and $D/T = 1/3$, $C/T = 1/4$	67
47. Heat Transfer Coefficient at Probe 2; HE-3 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/2$, $C/T = 1/3$ and $D/T = 1/2$, $C/T = 1/4$	68
48. $D/T = 1/3$, $C/T = 1/3$, D-6 Impeller	72
49. $D/T = 1/3$, $C/T = 1/4$, D-6 Impeller	73
50. $D/T = 1/2$, $C/T = 1/3$, D-6 Impeller	74

51.	D/T = 1/2, C/T = 1/4, D-6 Impeller	75
52.	Top View, D-6 Impeller	78
53.	Side View, D-6 Impeller	79
54.	D/T = 1/3, C/T = 1/3, P-4 Impeller	81
55.	D/T = 1/3, C/T = 1/4, P-4 Impeller	82
56.	D/T = 1/2, C/T = 1/3, P-4 Impeller	83
57.	D/T = 1/2, C/T = 1/4, P-4 Impeller	84
58.	D/T = 1/3, C/T = 1/3, HE-3 Impeller	88
59.	D/T = 1/3, C/T = 1/4, HE-3 Impeller	89
60.	D/T = 1/2, C/T = 1/3, HE-3 Impeller	90
61.	D/T = 1/2, C/T = 1/4, HE-3 Impeller	91
62.	Heat Transfer Coefficient at Probe B; $N_{Re} = 50,000$, Comparison among three impellers at D/T = 1/3, C/T = 1/3	93
63.	Heat Transfer Coefficient at Probe B; $N = 50,000$, Comparison among three impellers at D/T = 1/3, C/T = 1/4	94
64.	Heat Transfer Coefficient at Probe B; $N = 50,000$, Comparison among three impellers at D/T = 1/2, C/T = 1/3	95
65.	Heat Transfer Coefficient at Probe B; $N = 50,000$, Comparison among three impellers at D/T = 1/2, C/T = 1/4	96
66.	Heat Transfer Coefficient at Probe B; $N = 160,000$, Comparison among three impellers at D/T = 1/3, C/T = 1/3	97
67.	Heat Transfer Coefficient at Probe B; $N = 160,000$, Comparison among three impellers at D/T = 1/3, C/T = 1/4	98
68.	Heat Transfer Coefficient at Probe B; $N = 160,000$, Comparison among three impellers at D/T = 1/2, C/T = 1/3	99

69.	Heat Transfer Coefficient at Probe B; $N = 160,000$, Comparison among three impellers at $D/T = 1/2$, $C/T = 1/4$	100
70.	Heat Transfer Coefficient at Probe 1; $N = 50,000$, Comparison among three impellers at $D/T = 1/3$, $C/T = 1/3$	101
71.	Heat Transfer Coefficient at Probe 1; $N = 50,000$, Comparison among three impellers at $D/T = 1/3$, $C/T = 1/4$	102
72.	Heat Transfer Coefficient at Probe 1; $N = 50,000$, Comparison among three impellers at $D/T = 1/2$, $C/T = 1/3$	103
73.	Heat Transfer Coefficient at Probe 1; $N = 50,000$, Comparison among three impellers at $D/T = 1/2$, $C/T = 1/4$	104
74.	Heat Transfer Coefficient at Probe 1; $N = 160,000$, Comparison among three impellers at $D/T = 1/3$, $C/T = 1/3$	105
75.	Heat Transfer Coefficient at Probe 1; $N = 160,000$, Comparison among three impellers at $D/T = 1/3$, $C/T = 1/4$	106
76.	Heat Transfer Coefficient at Probe 1; $N = 160,000$, Comparison among three impellers at $D/T = 1/2$, $C/T = 1/3$	107
77.	Heat Transfer Coefficient at Probe 1; $N = 160,000$, Comparison among three impellers at $D/T = 1/2$, $C/T = 1/4$	108
78.	Heat Transfer Coefficient at Probe 2; $N = 50,000$, Comparison among three impellers at $D/T = 1/3$, $C/T = 1/3$	109
79.	Heat Transfer Coefficient at Probe 2; $N = 50,000$, Comparison among three impellers at $D/T = 1/3$, $C/T = 1/4$	110
80.	Heat Transfer Coefficient at Probe 2; $N = 50,000$, Comparison among three impellers at $D/T = 1/2$, $C/T = 1/3$	111
81.	Heat Transfer Coefficient at Probe 2; $N = 50,000$, Comparison among three impellers at $D/T = 1/2$, $C/T = 1/4$	112

82.	Heat Transfer Coefficient at Probe 2; $N = 160,000$, Comparison among three impellers at $D/T = 1/3$, $C/T = 1/3$	113
83.	Heat Transfer Coefficient at Probe 2; $N = 160,000$, Comparison among three impellers at $D/T = 1/3$, $C/T = 1/4$	114
84.	Heat Transfer Coefficient at Probe 2; $N = 160,000$, Comparison among three impellers at $D/T = 1/2$, $C/T = 1/3$	115
85.	Heat Transfer Coefficient at Probe 2; $N = 160,000$, Comparison among three impellers at $D/T = 1/2$, $C/T = 1/4$	116

LIST OF TABLES

TABLE	PAGE
1. Dimensionless Numbers	4
2. Heat Transfer to Jacketed Wall	11
3. The Summary of Experimental Runs	68
4. The Summary of Quick Survey	70
5. Heat Transfer Coefficient Data	117

LIST OF PLATES

PLATE	PAGE
I. Disk-blade Turbine (D-6)	18
II. Turbine Impeller with 45° Pitched Blades, Open Style (P-4)	19
III. Open-blade Fluid Foil Axial Impeller (HE-3)	20

Chapter I

INTRODUCTION

Heat transfer in agitated vessels is still one of the most common operations in the chemical and applied industries. The rate of heat transfer in mixing of liquids depends on the type of the agitator and the design of the vessel. In this research, the heat transfer at the wall of an agitated vessel with a dished bottom and four baffles was investigated. Three well known impeller types were studied. The contents (water) of the vessel were slowly cooled by natural convection from the outer surface. The heat transfer measurements were made by Micro-FoilTM heat flow sensors that were placed on the inside surface of the vessel. Thus, process side heat transfer coefficients were determined. Determining heat transfer coefficients by conventional thermocouple and heat balance technique is arduous and time consuming. The use of the thermopile style heat flux sensor to measure heat flow and temperature of the wall would be a useful and a viable means of making point to point local measurements. For data acquisition, MetraByte's EXP-16 data acquisition system was tested. Two BASIC programs were developed for data acquisition and determination of the heat transfer coefficients and other important values. The goal of this research was to provide a quick, accurate and efficient system for the determination of process side local heat transfer coefficients through the use of heat flow sensors and a PC based data acquisition system.

Chapter II

LITERATURE REVIEW

2.1 Dimensional Analysis

2.1.1 Navier-Stokes Equation

Fluid motion in an agitated system obeys the laws of conservation of mass and momentum which describe the velocity and pressure distributions within the fluid.

The following description is patterned after "Liquid Agitation" published by Chemineer, Inc. [7]. The Navier-Stokes equation for a Newtonian fluid provides the momentum balance in terms of local pressure and velocity:

$$\rho \frac{dv}{dt} = -g_c \nabla p + \mu \nabla^2 v + \rho g \quad (1)$$

Equation (1) can be rearranged into dimensionless form that involves ratios of the variables to characteristic quantities. A characteristic length would be the impeller diameter, D . The characteristic time is the reciprocal impeller rotational speed, $1/n$. The characteristic mass is the density, ρ , and the cube of the impeller diameter, D^3 . With these, the dimensionless length and time are:

$$x^* = x/D \quad (2)$$

$$y^* = y/D \quad (3)$$

$$z^* = z/D \quad (4)$$

$$t^* = tN \quad (5)$$

A dimensionless velocity can be defined from the ratio of actual velocity to the characteristic velocity:

$$v^* = v/ND \quad (6)$$

A dimensionless pressure can be developed from the gravitational conversion factor, g_c , and the characteristic quantities for length, time and mass:

$$p^* = \frac{(p - p_0)g_c}{\rho N^2 D^2} \quad (7)$$

To simplify the boundary condition, the reference pressure, p_0 , is selected.

The dimensionless numbers developed can be substituted into Eq. (1) and rearranged:

$$\frac{Dv^*}{Dt^*} = -\nabla^* p^* + \left[\frac{\mu}{D^2 N \rho} \right] \nabla^{*2} v^* + \left[\frac{g}{DN^2} \right] \frac{g}{g_c} \quad (8)$$

In this equation, two dimensionless groups (Reynolds and Froude numbers) appear. These dimensionless groups will be discussed later. Equation (8) indicates that the velocity and pressure distribution can be expressed as a function of Reynolds number and Froude number:

$$v^*(x^*, y^*, z^*, t^*) = f(N_{Re}, N_{Fr}) \quad (9)$$

$$p^*(x^*, y^*, z^*, t^*) = f(N_{Re}, N_{Fr}) \quad (10)$$

For a fully baffled tank system, gravitational effects can be ignored because the liquid surface is essentially flat. Velocity and pressure distributions are then described only as a function of the Reynolds number:

$$v^*(x^*, y^*, z^*, t^*) = f(N_{Re}) \quad (11)$$

$$p^*(x^*, y^*, z^*, t^*) = f(N_{Re}) \quad (12)$$

2.1.2 Dimensionless Numbers

There are ten dimensionless numbers for agitation which are accompanied by heat or mass transfer. These numbers are summarized in Table 1. Six of these are important (see Brodkey and Hershey [2]).

2.1.2.1 Reynolds Number

The Reynolds number represents the ratio of inertial to viscous forces. The Reynolds number for agitation is:

$$N_{Re} = D^2 N \rho / \mu \quad (13)$$

This Reynolds number is often called the Impeller - Reynolds number.

2.1.2.2 Power Number

The Power number is the relationship between the fluid pressure adjacent to the blade and power. The Power number is defined as:

$$N_{Po} = P g_c / (\rho N^3 D^5) \quad (14)$$

The power, P , is the product of rotational speed and applied torque. The torque is determined by integrating the pressure distribution over the surface of a flat-blade turbine. At high Reynolds number, inertial forces dominate over viscous forces; thus, viscous and gravitational forces in the Navier-Stokes equation become negligible. Equation (1) becomes:

$$\frac{Dv^*}{Dt^*} = - \nabla^* p^* \quad (15)$$

From Eq. (15), the pressure and velocity distributions are fixed for this case, since the Reynolds number is no longer a parameter. Therefore, the power number is a constant at high Reynolds number

TABLE 1. Dimensionless numbers*

Name	Symbol	Definition	Comments
Blend	N_b	$N\theta$	Related to uniform mixing or blending
Froude	N_{Fr}	$N^2 D/g$	Correlates with N_{Re} and N_{Po} for unbaffled systems
Nusselt	N_{Nu}	hT/k	Heat transfer to an agitation unit (jacketed or otherwise)
Power	N_{Po}	$P/(\rho N^3 D^5)$	Constant in baffled system if $N_{Re} > 10,000$
Prandtl	N_{Pr}	$c_p \mu/k$	Fluid properties for heat transfer correlation
Pumping	N_p	$Q/(ND^3)$	Related to impeller pumping capacities
Reynolds	N_{Re}	$D^2 N \rho/\mu$	Laminar flow if $N_{Re} < 10$; turbulent flow if $N_{Re} > 10,000$
Schmidt	N_{Sc}	$\mu/(\rho D_L)$	Fluid properties for mass transfer correlation
Sherwood	N_{Sh}	$k_L T/D_L$	Mass transfer between solute and solvent in an agitaion unit
Weber	N_{We}	$N^2 D^3 \rho/\sigma$	Related to surface behavior for two-phase system

* From reference [2], p.374.

because of a fixed, dimensionless pressure distribution along the impeller blade:

$$\frac{Pg_c}{\rho N^3 D^5} = \text{constant} \quad (16)$$

At low Reynolds numbers, the viscous term predominates; thus, one can neglect inertial and gravitational forces:

$$g_c \nabla p = \mu \nabla^2 v \quad (17)$$

The characteristic pressure is related to the viscous force per unit area, since momentum is neglected:

$$p^{**} = \frac{(p - p_o)g_c}{\mu N} \quad (18)$$

The Reynolds number is eliminated as a parameter and the dimensionless velocity and pressure distributions are constant. From this analysis, the viscous power number is:

$$p^{**} \propto \left(\frac{P}{ND^3} \right) \frac{g_c}{\mu N} = \frac{Pg_c}{\mu N^2 D^3} \quad (19)$$

For the two limiting cases, for high and low Reynolds number, the relationship between Reynolds number and Power number can be plotted on logarithmic coordinates, as shown in Fig. 1.

The Power number correlation depends mainly on the impeller design, since the Power number was developed from the pressure distribution along the impeller blade. Figure 2 shows the correlations of experimental data for four mixer designs. The turbine with disk mounted blades (curve 1 in Fig. 2) takes approximately 25 percent more power than the flat-blade style (curve 2). The pitched-blade turbine consumes considerably less power, but its flow patterns are different.

Fig. 1. Power Number (from ref. [7])

Fig. 2. Power Requirements for Agitated Systems (from ref. [7])

2.1.2.3 Froude Number

The Froude number involves the gravitational force and is used to account for the surface behavior (e.g., the central vortex) on the Power number:

$$N_{Fr} = N^2 D / g \quad (20)$$

2.1.2.4 Blend Number

The Blend number is:

$$N_b = N\theta \quad (21)$$

where θ is a measure of the time required for mixing a miscible fluid uniformly throughout the agitator tank volume.

2.1.2.5 Pumping Number

The pumping number is defined as a relation of the impeller pumping rate Q (e.g., the volumetric flow rate through the impeller area per unit time) to the speed and size of the impeller:

$$N_p = \frac{Q}{ND^3} \quad (22)$$

2.1.2.6 Weber Number

The Weber number is defined as a relation of inertial to surface forces. For agitation, it is:

$$N_{We} = N^2 D^3 \rho / \sigma \quad (23)$$

2.2 Heat Transfer in the Agitated System

The following description is from "Liquid Agitation" from Chemineer, Inc. [7].

2.2.1 Heat Transfer

Heat transfer in an agitated vessel is defined as:

$$q = U_i A_i (T_o - T_i) \quad (24)$$

where U_i = the overall heat transfer coefficient

A_i = the heat transfer area

T_o = temperature of heat transfer fluid

T_i = temperature of process fluid

If fouling factors are negligible, the overall heat transfer coefficient can be described in terms of three separated heat transfer resistances:

$$U_i = 1 / [(1/h_i) + (\Delta r/k_w)(A_i/A_w) + (1/h_o)(A_i/A_o)] \quad (25)$$

In Eq. (25), the first term is the inside film coefficient, h_i that is on the process liquid side of the surface. The second term is the conduction through the wall and the third term is the outside film coefficient.

2.2.2 Dimensional Analysis for Heat Transfer Coefficient

The inside or process side heat transfer coefficient can be defined from the heat flow, q , heat transfer area, A_i and the temperature difference between the inside wall and the bulk of the fluid, $(\Delta\theta)_i$:

$$h_i = q / A_i (\Delta\theta)_i \quad (26)$$

The heat flow, q can be determined from the temperature gradient at the inside wall of the vessel:

$$q = \iint_S (k \nabla \theta) dS_{\text{surface}} \quad (27)$$

From these two equation, a dimensionless form can be obtained:

$$\frac{h_i D}{k} \propto \iint_S \nabla^* \theta^* dS_{\text{surface}} \quad (28)$$

The left hand side of Eq. (28) is a Nusselt number for heat transfer and can be expressed as a function of the Reynolds and Prandtl numbers:

$$N_{Nu} = f(N_{Re}, N_{Pr}) \quad (29)$$

2.2.3 Correlations for Heat Transfer

A simple functional relationship to describe Eq. (29) is:

$$N_{Nu} = \alpha (N_{Re})^\beta (N_{Pr})^\gamma \quad (30)$$

The temperature difference is that between the bulk fluid and tank wall. The ratio of the bulk viscosity at the wall to the fluid is often included in the correlation to give

$$N_{Nu} = \frac{hD}{k} = k_2 (N_{Re})^a (N_{Pr})^b \left(\frac{\mu}{\mu_w} \right)^c \quad (31)$$

The constants in the Eq. (31) are shown in Table II from Uhl [3] for several different geometric conditions.

Another important empirical equation called the Chilton-Colburn analogy from reference [1] is defined as:

$$N_{Nu} = 0.0565 N_{Re}^{3/4} N_{Pr}^{1/3} \quad (32)$$

TABLE 2. Heat Transfer to Jacketed Wall*

Impeller type	Constants in Eq. (31)				Range of N_{Re}	Comments
	k_2	a	b	c		
Paddle	0.40	2/3	1/3	0.14	300 - 600,000	k_2 range from 0.36 to 0.40
Paddle	0.415	2/3	1/3	0.24	20 - 4000	ba f f l e d a n d unbaffled
Two curved-blade turbines						
	0.60	2/3	1/3	0.14	2000 - 800,000	
Pitched-blade turbine						
	0.44	2/3	1/3	0.24	80 - 120	l o w p o s i t i o n C = 4 inches
	0.53	2/3	1/3	0.24	20 - 120	i n t e r m e d i a t e position, C = 11 inches
Disk flat-blade turbine						
	0.54	2/3	1/3	0.14	40 - 300,000	unbaffled
	0.74	2/3	1/3	0.14	300 - 300,000	1, 2 , o r 4 baffles

*From reference [2], p. 383

Chapter III

EXPERIMENTAL

3.1 *Experimental Equipment*

The equipment for agitation involved the vessel to hold the fluid, impellers to provide the shear flow or mixing, a motor to drive the impeller, a tachometer to monitor the impeller speed and longitudinal wall baffle attached to the inside wall of the tank to aid in the mixing. In our work on heat transfer, heat flow sensors and thermocouple were needed to measure the temperature difference between the fluid and the wall and the heat flux into the wall. An A/D converter system by MetraByte Corp. was used to obtain the data and transfer it to a PC. Figure 3 shows the experimental apparatus.

3.1.1 *Agitated Vessel*

The cylindrical stainless steel container, obtained from Chemineer had a dished bottom. The vessel had heat flux sensors, mounted on the inside wall exactly over small local cooling regions designed to increase the heat flux. In this way, the bulk of the fluid was cooled slowly by natural convection and locally, in the region of the heat flux sensor, the cooling was much greater to allow accurate heat transfer coefficients to be measured. The sensors were mounted at different heights. Four baffles (at 90° each) were used. These could be easily

A : Path for the temperature of the mixed liquid
B : Path for the heat flux
C : Path for the wall temperature

Fig. 3. Experimental Apparatus

moved in the angular direction. Water was used for the fluid being mixed in the vessel as well as for cooling. The following definitions are used to define the vessel.

B : width of each baffle

C : distance from the tank bottom to the impeller center line

D : impeller diameter

T : inside diameter of tank

W : width of impeller

Z : depth of fluid in the tank

The actual dimensions are shown in Fig. 4.

3.1.2 Mixing Drive

An A-C/V*S drive by Reliance Electric was used. The A-C/V*S drive consists of two basic drive components: an adjustable frequency A-C/V*S drive controller and an induction motor. This drive operates on 220 VAC, three phase and 60 Hertz for a 5 horse power output. The speed range is 3 to 60 Hertz.

3.1.3 Input Digital Tachometer

The digital tachometer (TACHTROL) was used to measure the RPM of the agitator turbine. The tachometer has a 2 Hertz to 30KHertz frequency range and a quoted accuracy of about $\pm 0.03\%$. It is of the magnetic sensor type that counts the teeth on a sprocket wheel.

Fig. 4. The Dimensions of the Agitated Vessel

3.1.4 Impellers

The agitation characteristic and energy consumption strongly depend on the impeller design. Three different types of the impeller were used. The shapes of these are illustrated in Plates I-III. The six-blade disked turbine impeller [Rushton (D-6)] produces a radial flow pattern, as shown in Fig. 5. The turbine impeller with 45° pitched blades (P-4) and the open-blade hydrodynamic fluid foil axial impeller (HE-3) give axial flow patterns in baffled tanks, as shown in Fig. 6.

3.1.5 Heat Flux Sensor and Thermocouple

Rdf Micro-Foil heat flow sensors (Bottom and sensor 1: 20457-2 type, sensor 2: 20457-1 type) were used. This sensor consists of heat flow sensor part to measure the heat flow through the sensor and a thermocouple part to measure its temperature.

Typical specifications of the heat flow sensor and the thermocouple are:

Heat flow sensor:

Heat flow range: Up to 30,000 Btu/ft²h. For heat flow above 300 Btu/ft²h, special installation procedures are needed.

Polarity (for heat flow into surface): White - Positive (+), Red - Negative (-).

Typical sensitivity: 0.07 to 40 mV/Btu ft² sec (Actual values of those used in this work were Bottom: 3.3, Probe 1: 3.22, Probe 2: 1.19)

Typical response time: 0.02 to 0.5 secs.

Operating temperature range: -300°F to +500°F

Typical thermal impedance: 0.003 to 0.015 °F/Btu ft⁻²h⁻¹

Typical thermal capacitance : 0.01 to 0.05 Btu ft⁻²/°F

Plate I

Disk-blade Turbine (D-6)

Plate II

Turbine Impeller with 45° Pitched Blades, Open Style (P-4)

Plate III

Open-blade Fluid Foil Axial Impeller (HE-3)

Fig. 5. Flow Pattern for Flat-balde - Radial Flow (from ref. [2])

Fig. 6. Flow Pattern for Pitched-blade - Axial Flow (from ref. [2])

Thermocouple:

ANSI Type	Material	Polarity	Color
T	Copper	Pos. (+)	Blue
	Constantin	Neg. (-)	Red

Additional copper-constantin thermocouples were used in the vessel to measure the fluid temperature.

3.1.6 Data Acquisition System

A two board data acquisition system was used. Within the PC, a MetraByte DAS-8 board was installed. This was connected the second board mounted on the mixer stand. The second board, also by MetraByte was their EXP-16 multiplexer, specially designed for thermocouple level measurements. This board is an expansion multiplexer/amplifier system that can be used with any data acquisition system. Each EXP-16 board concentrates 16 differential analog input channels and feeds them into one analog channel of the PC board. The EXP-16 provides signal amplification, filtering and conditioning. The high grade instrumentation amplifiers in the EXP-16 provide user switch-selectable gains of 0.5, 1, 2, 10, 50, 100, 200 and 1000 plus user programming gain capability for special applications requiring specific gains. The 16 differential analog input channels are selected by a solid state 4 bit TTL/CMOS compatible address. Provision is made on the board for filtering and attenuation measuring current. A cold junction temperature is also available with this board, but was not used in our work, since some accuracy could be lost by its use. Fluid thermocouple types were used and each had its own ice bath junction provided. All

analog input connections are conveniently made on miniature screw connector strips.

3.2 Data Acquisition Programs

Two BASIC programs were used to determine the heat transfer coefficient, h , heat flux, Q/A , the bulk liquid temperature in the tank, the wall temperature, Reynolds number, Nusselt number and all physical properties.

3.2.1 Raw Data

A BASIC program called MIXEXP.BAS was used for obtaining the raw data from the experiments. It uses MetraByte's software calls to operate the MetraByte A/D converter. Means to average data to remove noise or to simply accumulate the raw data are available in this program. Three thousand data points are the maximum for the averaging mode, and up to 16 (0 to 15 differential inputs) channels can be used. The program list and the function of each mode are described in Appendix A.

3.2.2 Conversion

A BASIC program called NEWCON.BAS converts the raw data taken by the MIXEXP.BAS to appropriate variables and nondimensional numbers. The program list and an output example are shown in Appendix B. Both engineering and S.I. units were used because engineering units are still common in the U.S. mixing industry.

3.3 Experiment Procedure

Runs for the full field heat transfer measurements were made at 7 different angular positions between the baffles for each mixing configuration and at two Reynolds numbers. The runs in this work were made to establish a base-line of experimental data to evaluate the parameters of importance (impeller type, C/T, D/T, ϕ and Reynolds number) and to provide initial comparisons to literature data.

The runs made and the conditions were:

- a) three vertical sensors which have different locations: bottom (Probe B), side (Probe 1) and near top of the surface (Probe 2).
- b) two different D/T ratios (1/2, 1/3)
- c) two different C/T ratios (1/3, 1/4)
- d) three different types of impeller (D-6, P-4, HE-3)
- e) two different Reynolds numbers (N_{Re} : 50,000, 160,000)
- f) seven different baffle positions (to vary sensor position relative to tank): 2.85°, baffle positions just in front of the sensor and each 15° between; 87.15°, baffle positions just behind of the sensor. These baffle positions are shown in Fig. 7.

The experimental procedure was:

1. The tank contents were heated to 60°F. A Z/T of 1 was used. The process fluid was filtered through a filter.
2. The cooling water passed through an ice bath before it was distributed to each of the three sensor coolers used.
3. The raw data was taken at the conditions cited by using the averaging mode (one average of 5000 data points for each of 9 channel was used).

Fig. 7. Incremental Baffle rotation Settings

4. The raw data was converted to processing variables and non-dimensional numbers.

Chapter IV

RESULTS

The results of these wall measurements are shown as Figures 8-23, 24-35 and Figures 36-47. The specific conditions are shown in Table 3.

4.1 Preliminary Observations

A number of initial technical problems were overcome and the technique was demonstrated. The following lists the problem encountered and the solutions:

- 1) Using the non-averaging mode proved deficient because of serious noise limitations; thus, an averaging mode was used.
- 2) In the fabrication of the vessel, the individual sensor calibrations were mixed up and an averaged value had to be used). This contributed about 3% uncertainty.
- 3) The bearing for holding the shaft at the bottom was inadequate. A new steel encased bearing was made by Chemineer and has proved adequate.
- 4) The sensor at the bottom was broken by the impeller when the bearing failed and was replaced. The sensor at Probe 1 also failed for an unknown reason and was replaced. Actual calibration were used for the replacements, thus eliminating

Fig. 8. Heat Transfer Coefficient at Probe B; D-6 Impeller, $N_{Re} = 50,000$,
Comparison between $D/T = 1/3, C/T = 1/3$ and $D/T = 1/3, C/T = 1/4$

Fig. 9. Heat Transfer Coefficient at Probe B; D-6 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/2$, $C/T = 1/3$ and $D/T = 1/2$, $C/T = 1/4$

Fig. 10. Heat Transfer Coefficient at Probe 1; D-6 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/3, C/T = 1/3$ and $D/T = 1/3, C/T = 1/4$

Fig. 11. Heat Transfer Coefficient at Probe 1; D-6 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/2$, $C/T = 1/3$ and $D/T = 1/2$, $C/T = 1/4$

Fig. 13. Heat Transfer Coefficient at Probe 2; D-6 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/2$, $C/T = 1/3$ and $D/T = 1/2$, $C/T = 1/4$

Fig. 14. Heat Transfer Coefficient at Probe B; D-6 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/3, C/T = 1/3$ and $D/T = 1/3, C/T = 1/4$

Fig. 15. Heat Transfer Coefficient at Probe B; D-6 Impeller, $N_{Re} = 160,000$,
Comparison between $D/T = 1/2$, $C/T = 1/3$ and $D/T = 1/2$, $C/T = 1/4$

Fig. 16. Heat Transfer Coefficient at Probe 1; D-6 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/3, C/T = 1/3$ and $D/T = 1/3, C/T = 1/4$

Fig. 17. Heat Transfer Coefficient at Probe 1; D-6 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/2, C/T = 1/3$ and $D/T = 1/2, C/T = 1/4$

Fig. 18. Heat Transfer Coefficient at Probe 2; D-6 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/3, C/T = 1/3$ and $D/T = 1/3, C/T = 1/4$

Fig. 19. Heat Transfer Coefficient at Probe 2; D-6 Impeller, $N_{Re} = 160,000$,
Comparison between $D/T = 1/2$, $C/T = 1/3$ and $D/T = 1/2$, $C/T = 1/4$

Fig. 20. Heat Transfer Coefficient at Probe B; D-6 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/3$, $C/T = 1/3$ and $D/T = 1/2$, $C/T = 1/3$

Fig. 21. Heat Transfer Coefficient at Probe B; D-6 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/3, C/T = 1/4$ and $D/T = 1/2, C/T = 1/4$

Fig. 22. Heat Transfer Coefficient at Probe B; D-6 Impeller, $N_{Re} = 160,000$,
Comparison between $D/T = 1/3, C/T = 1/3$ and $D/T = 1/2, C/T = 1/3$

Fig. 23. Heat Transfer Coefficient at Probe B; D-6 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/3$, $C/T = 1/4$ and $D/T = 1/2$, $C/T = 1/4$

Fig. 24. Heat Transfer Coefficient at Probe B; P-4 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/3$, $C/T = 1/3$ and $D/T = 1/3$, $C/T = 1/4$

Fig. 25. Heat Transfer Coefficient at Probe B; P-4 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/2, C/T = 1/3$ and $D/T = 1/2, C/T = 1/4$

Fig. 26. Heat Transfer Coefficient at Probe 1; P-4 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/3, C/T = 1/3$ and $D/T = 1/3, C/T = 1/4$

Fig. 27. Heat Transfer Coefficient at Probe 1; P-4 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/2$, $C/T = 1/3$ and $D/T = 1/2$, $C/T = 1/4$

Fig. 28. Heat Transfer Coefficient at Probe 2; P-4 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/3$, $C/T = 1/3$ and $D/T = 1/3$, $C/T = 1/4$

Fig. 29. Heat Transfer Coefficient at Probe 2; P-4 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/2$, $C/T = 1/3$ and $D/T = 1/2$, $C/T = 1/4$

Fig. 30. Heat Transfer Coefficient at Probe B; P-4 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/3$, $C/T = 1/3$ and $D/T = 1/3$, $C/T = 1/4$

Fig. 31. Heat Transfer Coefficient at Probe B; P-4 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/2$, $C/T = 1/3$ and $D/T = 1/2$, $C/T = 1/4$

Fig. 32. Heat Transfer Coefficient at Probe 1; P-4 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/3$, $C/T = 1/3$ and $D/T = 1/3$, $C/T = 1/4$

Fig. 33. Heat Transfer Coefficient at Probe 1; P-4 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/2, C/T = 1/3$ and $D/T = 1/2, C/T = 1/4$

Fig. 34. Heat Transfer Coefficient at Probe 2; P-4 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/3$, $C/T = 1/3$ and $D/T = 1/3$, $C/T = 1/4$

Fig. 35. Heat Transfer Coefficient at Probe 2; P-4 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/2, C/T = 1/3$ and $D/T = 1/2, C/T = 1/4$

Fig. 36. Heat Transfer Coefficient at Probe B; HE-3 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/3, C/T = 1/3$ and $D/T = 1/3, C/T = 1/4$

Fig. 37. Heat Transfer Coefficient at Probe B; HE-3 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/2$, $C/T = 1/3$ and $D/T = 1/2$, $C/T = 1/4$

Fig. 38. Heat Transfer Coefficient at Probe 1; HE-3 Impeller, $N_{Re} = 50,000$,
Comparison between $D/T = 1/3$, $C/T = 1/3$ and $D/T = 1/3$, $C/T = 1/4$

Fig. 39. Heat Transfer Coefficient at Probe 1; HE-3 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/2$, $C/T = 1/3$ and $D/T = 1/2$, $C/T = 1/4$

Fig. 40. Heat Transfer Coefficient at Probe 2; HE-3 Impeller, $N_{Re} = 50,000$,
Comparison between $D/T = 1/3$, $C/T = 1/3$ and $D/T = 1/3$, $C/T = 1/4$

Fig. 41. Heat Transfer Coefficient at Probe 2; HE-3 Impeller, $N_{Re} = 50,000$, Comparison between $D/T = 1/2$, $C/T = 1/3$ and $D/T = 1/2$, $C/T = 1/4$

Fig. 42. Heat Transfer Coefficient at Probe B; HE-3 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/3$, $C/T = 1/3$ and $D/T = 1/3$, $C/T = 1/4$

Fig. 43. Heat Transfer Coefficient at Probe B; HE-3 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/2$, $C/T = 1/3$ and $D/T = 1/2$, $C/T = 1/4$

Fig. 44. Heat Transfer Coefficient at Probe 1; HE-3 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/3$, $C/T = 1/3$ and $D/T = 1/3$, $C/T = 1/4$

Fig. 45. Heat Transfer Coefficient at Probe 1; HE-3 Impeller, $N_{Re} = 160,300$, Comparison between $D/T = 1/2, C/T = 1/3$ and $D/T = 1/2, C/T = 1/4$

Fig. 46. Heat Transfer Coefficient at Probe 2; HE-3 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/3$, $C/T = 1/3$ and $D/T = 1/3$, $C/T = 1/4$

Fig. 47. Heat Transfer Coefficient at Probe 2; HE-3 Impeller, $N_{Re} = 160,000$, Comparison between $D/T = 1/2$, $C/T = 1/3$ and $D/T = 1/2$, $C/T = 1/4$

TABLE 3. The Summary of Experimental Runs

Impeller	C/T	D/T	Figures
D-6	1/3	1/3	8, 10, 12, 14, 16, 18
D-6	1/4	1/3	
D-6	1/3	1/2	9, 11, 13, 15, 17, 19
D-6	1/4	1/2	
P-4	1/3	1/3	24, 26, 28, 30, 32, 34
P-4	1/4	1/3	
P-4	1/3	1/2	25, 27, 29, 31, 33, 35
P-4	1/4	1/2	
HE-3	1/3	1/3	36, 38, 40, 42, 44, 46
HE-3	1/4	1/4	
HE-3	1/3	1/2	37, 39, 41, 43, 45, 47
HE-3	1/4	1/2	

those uncertainties. Probe 2 has not been replaced, so that the uncertainty cited above remains.

- 5) The first experimental heat transfer coefficients measured were two to three times lower than expected. It was established that the thermocouple was located in the middle of the sensor, not near the surface. Thus the results had to be corrected for the thermal resistance of material used in the sensor construction. The low coefficient was also caused by the water in the inlet line containing rust, which when deposited on the sensors, caused additional resistance on the surface. A filter was installed at the inlet of the water source and used to fill the vessel. The sensors were wiped clean before each run.

4.2 Introduction to detail measurements

The figures give the heat transfer coefficients plotted as a function of sensor angular position. Generally, the figures have been selected for A-B comparisons. However, a quick survey is present as Table 4 where every run is tabulated. The heat transfer coefficient values reported here are the average of positions 30, 45 and 60°; These sensors are away from the influence of the baffles.

4.3 Rushton D-6 impeller

The flow patterns for the D-6 impeller are shown in Fig. 48-51.

A C/T ratio of 1/4 generally gives a greater heat transfer coefficient (0 to 20%) at the bottom of the tank than a ratio of 1/3 because the impeller is located closer to the sensor at the bottom

TABLE 4. Summary of Quick Survey

Row	Impeller Type (D/T, C/T)	N_{Re}	Heat Transfer Coeff. (Btu/hr-ft ² -°F) Average of 30, 45, 60° positions		
			Probe B	Probe 1	Probe 2
1	D-6 (1/3, 1/3)	50,000	368.	579.	519.
		160,000	973.	1486.	1633.
2	D-6 (1/3, 1/4)	50,000	517.	403.	393.
		160,000	1274.	873.	950.
3	D-6 (1/2, 1/3)	50,000	243.	451.	539.
		160,000	384.	1702.	1485.
4	D-6 (1/2, 1/4)	50,000	253.	375.	536.
		160,000	570.	1284.	1382.
5	P-4 (1/3, 1/3)	50,000	944.	311.	498.
		160,000	2006.	765.	1195.
6	P-4 (1/3, 1/4)	50,000	1288.	340.	544.
		160,000	5109.	1409.	1410.
7	P-4 (1/2, 1/3)	50,000	540.	305.	700.
		160,000	1610.	594.	1568.
8	P-4 (1/2, 1/4)	50,000	1083.	424.	499.
		160,000	2282.	1165.	1101.
9	HE-3 (1/3, 1/3)	50,000	394.	175.	299.
		160,000	1464.	503.	692.
10	HE-3 (1/3, 1/4)	50,000	581.	202.	291.
		160,000	3920.	569.	782.
11	HE-3 (1/2, 1/3)	50,000	340.	181.	231.
		160,000	1221.	495.	558.
12	HE-3 (1/2, 1/4)	50,000	413.	205.	247.
		160,000	2105.	561.	601.

Fig. 48. $D/T = 1/3$, $C/T = 1/3$, D-6 Impeller

Fig. 49. $D/T = 1/3$, $C/T = 1/4$, D-6 Impeller

Fig. 50. $D/T = 1/2$, $C/T = 1/3$, D-6 Impeller

Fig. 51. $D/T = 1/2$, $C/T = 1/4$, D-6 Impeller

(Figs. 8, 9, 14 & 15 and Table 4, rows 1 & 2 and 3 & 4). The induced velocity over the sensor should be greater (and thus the heat transfer) for the C/T of 1/4 case. However, for the large impeller at the low Reynolds number (Fig. 9 and Table 4, rows 3 & 4), the coefficient is the lowest observed in these experiments and the differences are slight. This is probably a result of the bottom sensor being in a relatively stagnant area as shown in Fig. 51.

A C/T ratio of 1/3 gives a greater heat transfer coefficient to Probe 1 and Probe 2 than a ratio of 1/4 (0 to 40%) because of the relative location of the impeller to the sensor (Figs. 10-13 and Figs. 16-19 and Table 4, rows 1 & 2 and 3 & 4). For Probe 2 with the large impeller the differences are small (Fig. 13 and 19 and Table 4, rows 3 & 4); however, the values of the heat transfer coefficients themselves are at the higher end of the ranges. The reason for the small difference at Probe 2 is probably caused by increased turbulence caused by the large impeller at its higher location. The mixing is as good as possible, and the coefficients are near a limiting level (Figs. 50 and 51). Of course, there is a large effect of the increased Reynolds number as seen by comparing Figs. 13 and 19 (a factor of 2.5).

Figures 20 to 23 are cross plots of the data for the bottom sensor. Plotted on each figure are the two impeller sizes at a given positions and Reynolds numbers. At the same Reynolds number and position, the 7.5 inches diameter impeller ($D/T = 1/2$) gave a smaller heat transfer coefficient to Probe B than the 5 inches diameter impeller (25 to 50%). The two different size impellers gave somewhat similar heat transfer coefficients or Nusselt numbers to the side sensor (Probe 1) and the top

sensor (Probe 2) when compared at the same Reynolds number and position (Figs. 10 & 11, 12 & 13, 16 & 17 and 18 & 19 and Table 4, rows 1 - 4). The differences are small at a C/T of 1/3, but can be up to 30% at a C/T of 1/4.

Near the baffles, the flow can be complex. Figure 52 suggests such a flow. From this figure, the coefficients should be higher for 87.15° than 2.85° , since the velocity over the sensor should be higher. Of course, this could only apply to Probe 1 and Probe 2 where the baffles exist and not at Probe B which is not in the proximity of the baffles. This was observed at $D/T = 1/3$ for all cases (Figs. 10, 12, 16 and 18). At $D/T = 1/2$, it was also true for Probe 2, but not at Probe 1, where the values are much closer. This suggest that the flow for the Probe 1 case for the large impeller is more like Fig. 53 than 52, i.e., more a flow over the sensor along the baffle rather than over the baffle. In contrast, because the flow must change in the vicinity of the surface (Probe 2), the flow is more over the baffle at that position.

4.4 P-4 Impeller

The pitched blade impeller produces an axial flow in the vessel. Thus, these results are expected to be quite different than for the radial (D-6) type impeller. The results with the P-4 impeller are:

A C/T ratio of 1/4 generally gives a greater heat transfer coefficient to the bottom than a ratio of 1/3 (30 to 40%) which was the same results as for D-6 impeller (Figs. 24, 25, 30 and 31 and Table 4, rows 5 & 6 and 7 & 8). This, no doubt is due to the closer proximity of the impeller to the sensor for the 1/4 case. For the bottom sensor, the

2.85 DEG.

87.15 DEG.

Fig. 52. Top View, D-6 Impeller

2.85 DEG

87.15 DEG

Fig. 53. Side View, D-6 Impeller

flow results in doubling of the heat transfer coefficients (Figs. 24 & 25 and 30 & 31 and Table 4, rows 5 & 6 and 7 & 8).

A C/T ratio of $1/4$ gives a greater heat transfer coefficient to Probe 1 than a ratio of $1/3$ (up to 50%) because a ratio of $1/4$ gives a greater axial fluid flow along Probe 1 (Figs. 26 & 27 and 32 & 33 and Table 4, rows 5 & 6 and 7 & 8). However, for the lower Reynolds number, the difference is smaller. The exact reason for this is unknown. At this Reynolds number, the smaller impeller gives nearly the same values, while the larger impeller gives a 30% increase at the lower position. When the impeller is located near the bottom ($C/T = 1/4$) the flow into the dished bottom is reversed and flows upward along the wall (Figs. 56 and 57). When the impeller is higher up ($C/T = 1/3$) the flow is dissipated as it flows to the bottom and retards the upward flow along the wall (Figs. 54 and 55). The results are nearly the same at both positions for the small impeller and only 25% or so for the large impeller.

Probe 2 is located just below the fluid surface. The flow in this region must be complex indeed. For the large impeller, a C/T ratio of $1/3$ gives a 25% greater heat transfer coefficient to Probe 2 than the $1/4$ position (Figs. 29 and 35 and Table 4, rows 7 & 8). However, for the small impeller, the effect is reversed, even though there is only a 10% or so difference (Figs. 28 and 34 and Table IV, rows 5 & 6). The differences are smaller for the lower Reynolds number. Even though the variation is relatively small, the larger impeller can apparently induce more flow even at Probe 2. It should be remembered that these effects are small indeed, since the change in Reynolds number from 50,000 to

Fig. 54. $D/T = 1/3$, $C/T = 1/3$, P-4 Impeller

Fig. 55. $D/T = 1/3$, $C/T = 1/4$, P-4 Impeller

Fig. 56. $D/T = 1/2$, $C/T = 1/3$, P-4 Impeller

Fig. 57. $D/T = 1/2$, $C/T = 1/4$, P-4 Impeller

160,000 causes a doubling of the coefficient as compared to a nearly negligible 10% caused by impeller size and position (Figs. 28 & 29 and Figs. 34 & 35 and Table 4, rows 5, 6, 7 and 8).

At the same Reynolds number and position, the 7.5 inches diameter impeller ($D/T=1/2$) gives a smaller heat transfer coefficient to the bottom than the 5 inches diameter impeller ($D/T=1/3$) for similar reason as with the D-6 impeller case (Table 4, rows 5 & 7 and 6 & 8). Recall that the larger impeller rotates much slower than the smaller to maintain the same Reynolds number. Thus, the actual velocity one that sensor could be lower. The different size of impellers give similar heat transfer coefficients to the side sensor (Probe 1) and the top sensor (Probe 2). Again, the variation with Reynolds number is far more important being a doubling or more in going for 50,000 to 160,000.

The heat transfer coefficient at the bottom sensor (Probe B) shows little influenced of the baffle (Figs. 24 & 25 and 30 & 31). The heat transfer coefficients at Probe 1 and Probe 2 are higher near the baffle for the same reason as the D-6 impeller case (Figs. 26-29 and 32-35).

4.5 HE-3 impeller

Virtually, the same results were obtained for the HE-3 impeller as for the P-4 impeller.

A C/T ratio of $1/4$ gives essentially the same heat transfer coefficient to the bottom of the tank as the $1/3$ ratio. This is a different result than obtained for the D-6 and P-4 impeller cases (Figs. 36 & 37 and 42 & 43 and Table 4, rows 9 & 10 and 11 & 12). The difference between the P-4 and HE-3 designs must be due to the axial

downflow dispersion. For the HE-3 impeller, the downflow is like a circular cylinder with little dispersion. Thus, the flow at the bottom is independent of the impeller location. For the P-4, the dispersion results in a decreased velocity at the bottom for the impeller location higher up.

A C/T ratio of $1/4$ gives essentially the same heat transfer coefficient to Probe 1 and Probe 2 as the $1/3$ ratio. This is the different result as obtained for the P-4 impeller, where the coefficient is often doubled. Once again, the variation with Reynolds number is important being more than doubling at Probe 2, tripling at probe 1, and 2 to 4 times at the bottom (Probe B) (Figs 42-47 and Table 4, rows 9 - 12).

At the bottom (Probe B), for the same Reynolds number and position, the 7.5 inches diameter impeller ($D/T = 1/2$) gives a smaller heat transfer coefficient than the 5 inches diameter impeller ($D/T = 1/3$), again for the same reason as cited earlier for the D-6 and P-4 impeller cases. For Probe 1 and Probe 2, two different sizes of impellers give similar heat transfer coefficients.

For the HE-3 impeller, the heat transfer coefficients variation with radial position at all three different heights is not affected by the baffles; i.e., there is little dependence on angular position.

The results imply that the HE-3 flow near the wall is far more vertical than for the P-4. The observation that the He-3 impeller results are not dependent on the baffle position strongly suggests that the flow direction is not over the baffle, but rather along the baffle. This explains why the impeller location is not important; i.e., the

upward flow for both sizes and positions must be similar. Due to Probe 2 being near the complex flow at the surface, the results obtained are different than for Probe 1, i.e., 50% or so greater. Note, however, that the independence of the values at Probe 2 with both impeller size and position, suggests again flow along the baffle.

Finally, it is not known from this work why the dispersion or spread of the downward flow is different for the P-4 and HE-3 impeller. However, it is logical to assume that this is a result of the nature of the wing-tip vortex that is known to exist on both impellers. Tatterson, Brodkey et al. have shown that for the P-4 impeller, there exists a high speed outward flowing jet that forms along the back of the P-4 impeller. This jet could push the wing-tip vortex outward. Apparently, the HE-3 construction modifies this jet to be less outward flowing. The flow patterns for HE-3 impeller are shown in Fig. 58 - Fig. 61 at each different D/T and C/T ratios. Further visual studies could be useful here.

Fig. 58. $D/T = 1/3$, $C/T = 1/3$, HE-3 Impeller

Fig. 59. $D/T = 1/3$, $C/T = 1/4$, HE-3 Impeller

Fig. 60. $D/T = 1/2$, $C/T = 1/3$, HE-3 Impeller

Fig. 61. $D/T = 1/2$, $C/T = 1/4$, HE-3 Impeller

Chapter V

DISCUSSION

Inter-comparisons among the three impellers are made in Figs. 62-85. Since the P-4 and HE-3 impellers produce axial flow, it is recognized that the D-6 impeller performs a different function than either the P-4 or HE-3 and that the P-4 and HE-3 are similar to each other. They give greater heat transfer to the bottom sensor than the D-6 impeller (Figs. 62-69). The HE-3 is a highly efficient and provides more of an axial flow than the P-4 impeller. However, the total flow, even though more axial, is probably less because the P-4 impeller has 4 blades, while the HE-3 impeller has only 3 blades. In addition, the P-4 impeller blades are wider than the HE-3 impeller blades. Thus, the P-4 impeller often gives higher flow and heat transfer coefficients than the HE-3 impeller. The P-4 impeller gives higher heat transfer coefficient to the bottom by a factor of 2 or more. However, once again the Reynolds number is a big factor with a difference of a factor of 2 or more from the low to the high numbers.

The D-6 impeller would be expected to give excellent heat transfer results to Probe 1. Recall, however, the P-4, located at $C/T = 1/4$ gave a high upward flow along the wall and excellent values of heat transfer coefficient (Figs. 71-73 and 75-77). Thus, it is not surprising to find that the P-4 and D-6 impellers give similar heat transfer coefficient to

Fig. 62. Heat Transfer Coefficient at Probe B; $N_{Re} = 50,000$, Comparison among three impellers at $D/T = 1/3$, $C/T = 1/3$

Fig. 63. Heat Transfer Coefficient at Probe B; $N_{Re} = 50,000$, Comparison among three impellers at $D/T = 1/3$, $C/T = 1/4$

Fig. 64. Heat Transfer Coefficient at Probe B; $N_{Re} = 50,000$, Comparison among three impellers at $D/T = 1/2$, $C/T = 1/3$

Fig. 65. Heat Transfer Coefficient at Probe B; $N_{Re} = 50,000$, Comparison among three impellers at $D/T = 1/2$, $C/T = 1/4$

Fig. 66. Heat Transfer Coefficient at Probe B; $N_{Re} = 160,000$, Comparison among three impellers at $D/T = 1/3$, $C/T = 1/3$

Fig. 67. Heat Transfer Coefficient at Probe B; $N_{Re} = 160,000$, Comparison among three impellers at $D/T = 1/3$, $C/T = 1/4$

Fig. 68. Heat Transfer Coefficient at Probe B; $N_{Re} = 160,000$, Comparison among three impellers at $D/T = 1/2$, $C/T = 1/3$

Fig. 69. Heat Transfer Coefficient at Probe B; $N_{Re} = 160,000$, Comparison among three impellers at $D/T = 1/2$, $C/T = 1/4$

Fig. 70. Heat Transfer Coefficient at Probe 1; $N_{Re} = 50,000$, Comparison among three impellers at $D/T = 1/3$, $C/T = 1/3$

Fig. 71. Heat Transfer Coefficient at Probe 1; $N_{Re} = 50,000$, Comparison among three impellers at $D/T = 1/3$, $C/T = 1/4$

Fig. 72. Heat Transfer Coefficient at Probe 1; $N_{Re} = 50,000$, Comparison among three impellers at $D/T = 1/2$, $C/T = 1/3$

Fig. 73. Heat Transfer Coefficient at Probe 1; $N_{Re} = 50,000$, Comparison among three impellers at $D/T = 1/2$, $C/T = 1/4$

Fig. 74. Heat Transfer Coefficient at Probe 1; $N_{Re} = 160,000$, Comparison among three impellers at $D/T = 1/3$, $C/T = 1/3$

Fig. 75. Heat Transfer Coefficient at Probe 1; $N_{Re} = 160,000$, Comparison among three impellers at $D/T = 1/3$, $C/T = 1/4$

Fig. 76. Heat Transfer Coefficient at Probe 1; $N_{Re} = 160,000$, Comparison among three impellers at $D/T = 1/2$, $C/T = 1/3$

Fig. 77. Heat Transfer Coefficient at Probe 1; $N_{Re} = 160,000$, Comparison among three impellers at $D/T = 1/2$, $C/T = 1/4$

Fig. 78. Heat Transfer Coefficient at Probe 2; $N_{Re} = 50,000$, Comparison among three impellers at $D/T = 1/3$, $C/T = 1/3$

Fig. 79. Heat Transfer Coefficient at Probe 2; $N_{Re} = 50,000$, Comparison among three impellers at $D/T = 1/3$, $C/T = 1/4$

Fig. 80. Heat Transfer Coefficient at Probe 2; $N_{Re} = 50,000$, Comparison among three impellers at $D/T = 1/2$, $C/T = 1/3$

Fig. 81. Heat Transfer Coefficient at Probe 2; $N_{Re} = 50,000$, Comparison among three impellers at $D/T = 1/2$, $C/T = 1/4$

Fig. 82. Heat Transfer Coefficient at Probe 2; $N_{Re} = 160,000$, Comparison among three impellers at $D/T = 1/3$, $C/T = 1/3$

Fig. 83. Heat Transfer Coefficient at Probe 2; $N_{Re} = 160,000$, Comparison among three impellers at $D/T = 1/3, C/T = 1/4$

Fig. 84. Heat Transfer Coefficient at Probe 2; $N_{Re} = 160,000$, Comparison among three impellers at $D/T = 1/2$, $C/T = 1/3$

Fig. 85. Heat Transfer Coefficient at Probe 2; $N_{Re} = 160,000$, Comparison among three impellers at $D/T = 1/2$, $C/T = 1/4$

Probe 1 at the C/T value of 1/4. The HE-3 impeller gives the smallest coefficient nearly independent of position except for the bottom sensor. Here, once again, the Reynolds number is the most important factor, with nearly a factor of 3 from the low to high values.

For a C/T ratio of 1/3 case, the D-6 impeller generally gives the greatest heat transfer coefficient to Probe 1 and the HE-3 impeller gives the smallest. The difference can be as much as a factor of 5 at the higher Reynolds numbers (Figs. 70 & 72 and 74 & 76).

Probe 2 is complex, being near the surface. The D-6 and P-4 impellers generally give high heat transfer coefficient at Probe 2 (Figs. 80-85). At the lower Reynolds number, the P-4 gives higher values (Figs. 78-81) and at the high Reynolds number, the D-6 is higher (Figs. 82-85). The differences are not as great, being generally less than 30% or so. At the higher Reynolds number, the coefficients are larger and the effect easier to observe. The percentage differences, however, remain about the same, with the big effect once again being the Reynolds number level.

For the D-6 (Rushton) impeller, the experimental heat transfer coefficient data obtained in this study are consistent with each other, and quite reasonable when compared with the calculated local heat transfer coefficients based on Fort et al. [1], the boundary layer equation [2], or the overall heat transfer coefficient for the entire vessel [3]. Table 5 summarized the results. From the table, one can see that in general the measured coefficients compare well with the estimated. For example, at the low Reynolds number the comparison has a standard deviation between the experimental and calculated of 66.04

Table 5. Heat Transfer Coefficient Data

Impeller Type (C/T, D/T)	N_{Re}	h_{exp} (Btu/hr-ft ² -°F)		h_{calc}		SD [*] ± (%)	
		1	2	1	2	1	2
D-6 (1/3, 1/3)	50,000	591.	565.	474.	478.	10.1	26.7
	160,000	1523.	1959.	1034.	1038.	5.6	26.4
D-6 (1/3, 1/4)	50,000	459.	431.	477.	480.	19.5	13.0
	160,000	915.	1028.	1037.	1042.	17.6	31.0
D-6 (1/2, 1/3)	50,000	466.	583.	523.	524.	20.4	40.2
	160,000	1786.	1685.	1059.	1062.	23.1	40.1
D-6 (1/2, 1/4)	50,000	402.	594.	512.	513.	25.8	45.3
	160,000	1475.	1769.	1071.	1072.	38.0	30.1

* The ± is the experimental standard deviation for all position including those near the baffles.

(Btu/hr-ft²-°F) which is $\pm 12\%$ based on the experimental value. The corresponding numbers for the high Reynolds number are 499.65 and 29.79. Note that variation with position represents anywhere from 10 to 40% (last two columns of Table 5) of that reported above.

For P-4 and HE-3 impellers, the experimental heat transfer coefficient data show quite reasonable results as expected. Unfortunately, there are no literature data for these impellers to be compared with these experimental data. Only two literature values for P-4 impeller are shown in Table 2. However, these cannot be used, since they are for very low Reynolds numbers.

REFERENCES

- [1] Fort, I. J. Placek, F. Strek, Z. Jaworski and J. Karcz, "Heat and Momentum transfer in the wall region of a cylindrical vessel mixed by a turbine impeller", *Col. Czech. Chem. Commun.*, 44, 684-698 (1979)
- [2] Brodkey, R. S. and H.C. Hershey, *Transport Phenomena; A Unified Approach*, McGraw-Hill (1988)
- [3] Uhl, V. W., "Mechanically Aided Heat Transfer", in *Mixing; Theory and Practice, Vol. I*, Academic Press, Uhl & Grey eds., (1966)
- [4] Gary Brooks and Gous-Jen Su, "Heat transfer in agitated kettles", *Chemical Engineering Progress*, 55, 10, 54-57 (1959)
- [5] F. S. Chapman and F. A. Holland, "Heat-Transfer Correlations in jacketed Vessels", *Chemical Engineering*, 72, 4, 175-184, (1965)
- [6] V. W. Uhl, "Heat Transfer to Viscous Materials in jacketed Agitated Kettles", *Chemical Engineering Progress Symposium Series*, 51, 17, 93-107 (1952)
- [7] Chemineer. Co., "Liquid Agitation", MacGraw-Hill, (1985)
- [8] F. Kupcik, "Heat transfer at the bottom and at the walls of agitated vessels", *International Chemical Engineering*, 16, 1, 91-96 (1976)
- [9] Ackley, R. J, The Pfaudler Co., Div. of Pfaudler Permutit Inc., "Film coefficients of heat transfer for agitated process vessels", *Chemical Engineering*, 69, 17, 133-140 (1960)
- [10] F. S. Chapman and F. A. Holland, "Heat transfer correlations for agitated liquids in process vessels", *Chemical Engineering*, 72, 2, 155-162 (1965)
- [11] Reinhold Poggeemann, Artur Steiff and Paul-Michael Weinspach, "Heat transfer in agitated vessels with single-phase liquids", *Ger. Chem. Eng.*, 3, 163-174 (1980)

- [12] K. L. Man, M. F. Edwards and G. T. Polley, "A study of local heat transfer coefficients in agitated vessels", *Fluid Mixing II*, 193-207 (1984)
- [13] Rasheed S. Al-Ameeri and Naima A. Ahmad, "Effect of drag-reducing additives on mixing and residence times in continuous-flow stirred tanks", *J. Univ. Kuwait (Sci)*, 14, 233-242 (1987)
- [14] A. Q. Quraishi, R. A. Mashelkar and J. J. Ulbrecht, "Influence of drag reducing additives on mixing and dispersing in agitated vessels", *AIChE J.*, 23, 4, 487-500 (1977)
- [15] F. Strek and S. Masiuk, "Heat transfer in liquid mixers", *International Chemical Engineering*, 7, 4, 693-702 (1967)
- [16] F. Strek, S. Masiuk, G. Gawor and R. Jagiello, "Heat transfer in mixers for liquids (studies of propeller agitators)", *International Chemical Engineering*, 5, 4, 695-710 (1965)
- [17] M. Yianneskis, Z. Popiolek and J. H. Whitelaw, "An experimental study of the steady flow characteristics of stirred reactors", *Fluids Section, Mech. Eng. Dept., College of Science and Technology* (1986)
- [18] James Y. Oldshue, "Fluid Mixing in 1989", *Chemical Engineering Progress*, 85, 33-42 (1989)
- [19] M. Buerli and W. Regenass, "Power and heat transfer to agitated suspensions: Use of heat flow calorimetry", *Shorter Communications*, 36, 784-787 (1980)
- [20] J. R. Bourne, O. Dossenbach and T. Post, "Local and average mass and heat transfer generated by pfaudler-type impellers", *Fluid Mixing II*, 233-242 (1984)
- [21] F. Kupcik, "Heat transfer at the wall and the bottom of agitated vessels, Part II", *International Chemical Engineering*, 15, 4, 658-664 (1975)

Appendix A
Program List for Obtaining the Raw Data

```

10 '*****
20 '*                               MIXEXP.BAS                               *
30 '*                               *                                       *
40 '*      Program for data acquisition using MetraByte Mode 4 or 5       *
50 '*                               Modification of earlier Haake program   *
60 '*                               *                                       *
70 '*      MetraByte Corporation, modified by Haam                        7-12-89 *
80 '*****
90 '
100 SCREEN 0,0,0 : KEY OFF : WIDTH 80
110 '
120 CLS
130 PRINT"           Mixing data acquisition for BASICA"
140 PRINT "   "
150 '
160 '--- Step 1:  Initialize DAS-8 PGA with mode 0 -----
170 '
180 NN=0
190 NNINIT=0
200 NNNN=0
210 C=0
220 CLEAR, 49152!
230 DEF SEG = 0      'Ready to read BASIC's working segment location
240 SG = 256*PEEK(&H511) + PEEK(&H510)
250 SG = SG + 49152!/16 'Load location at end of workspace
260 DEF SEG = SG
270 BLOAD "DAS8.BIN",0 'Load driver routine
280 DAS8 = 0          'Load offset = 0
290 DIM D%(15)        'Data transfer array variable
300 DIM T(15)
310 DIM A%(5000)
320 DIM TS(100)
330 DIM X(16,100)
340 DIM GAIN(16)
350 NSTOP=0
360 CLS: INPUT "Enter Base address or CARRAGE RETURN if 300 Hex is
              ok ",B%
370 IF B%=0 THEN B%=&H300 'Set this for correct base address
380 D%(0) = B%           'I/O address of DAS-8 (change to suit)
390 MD% = 0              'initialize mode
400 FLAG% = 0            'declare error variable
410 CALL DAS8 (MD%, D%(0), FLAG%)
420 IF FLAG% <> 0 THEN PRINT "Error in initialization":STOP
430 '
440 '----- Step 2: Select the channels to scan on the DAS8-PGA board-
450 '
460 CLS
470 PRINT"           The channels will be stored in array A%"
480 PRINT"           in the order scanned"
490 PRINT"           A%(0) = channel 1 data"
500 PRINT"           A%(1) = channel 2 data"
510 PRINT"           A%(2) = channel 3 data"

```



```

520 PRINT"                                A%(3) = channel 1 data etc."
530 PRINT " "
540 PRINT "*****"
550 PRINT "*"
560 PRINT "*"          FOR EXP-16 ONLY USE SET BOTH CHANNELS TO 1
570 PRINT "*"
580 PRINT "*****"
590 PRINT " "
600 PRINT"          ALTERNATELY USE CHANNELS 2 TO 7 AND STAT-08 BOARD"
610 PRINT"          DO NOT USE CHANNEL 1 UNDER THESE CONDITIONS"
620 PRINT " "
630 INPUT "          Lower channel scan limit (0-7 differential)? : ",LL%
640 INPUT "          upper channel scan limit (0-7 differential)? : ",UL%
650 D%(0) = LL%          'lower limit
660 D%(1) = UL%          'upper limit
670 CPGA = UL%-LL%+1
680 PRINT " "
690 PRINT "    You are using "CPGA" channels, verify if this is correct!"
700 PRINT " "
710 PRINT "          ***** IS IT OK, IF type CONT *****"
720 STOP
730 IF LL% < > 1 GOTO 930
740 PRINT " "
750 PRINT "*****"
760 PRINT "*"
770 PRINT "*" THE CHANNELS ON THE EXP-16 BOARD MUST BE SELECTED
780 PRINT "*" ONCE DONE, THE DATA IS IMMEDIATELY ACQUIRED BY MODE 4
790 PRINT "*" AND PROCESSED INTO A FINAL FILE
800 PRINT "*"
810 PRINT "*"          0 to 15 differential inputs
820 PRINT "*"
830 PRINT "*****"
840 PRINT " "
850 INPUT "          Lower channel scan limit (0-15 on the EXP-16)? : ",LM%
860 INPUT "          upper channel scan limit (0-15 on the EXP-16)? : ",UM%
870 CEXP = UM%-LM%+1
880 PRINT " "
890 PRINT "          You are using "CEXP" channels ON THE EXP-16!"
900 PRINT " "
910 PRINT "          ***** IS IT OK, IF type CONT *****"
920 STOP
930 IF LL%=1 THEN CHAN=CEXP ELSE CHAN=CPGA
940 MD%=1
950 CALL DAS8(MD%,D%(0),FLAG%)
960 IF FLAG%<>0 THEN PRINT "Error in setting scan limits # ";FLAG%:STOP
970 '
980 IF LL%=1 THEN GOTO 1240
990 '----- Step 3: Set timer rate -----
1000 '
1010 MD% = 10          'Mode 10 for setting counter configuration
1020 D%(0) = 2          'Operate on counter #2
1030 D%(1) = 3          'Configuration #2 = rate generator

```

```

1040 CALL DAS8 (MD%, D%(0), FLAG%)
1050 IF FLAG% <> 0 THEN PRINT "Error in setting counter 2
      configuration":STOP
1060 '
1070 'Prompt user for desired sample rate
1080 CLS
1090 PRINT"      The PGA uses Mode 5: < 3000 conversions/sec total."
1100 PRINT"      The EXP-16 uses Mode 4: single A/D conv. and inc"
1110 PRINT " "
1120 INPUT " Enter desired sample rate per channel (Hz/channel) : ",F
1130 F = F*CPGA
1140 ' Output frequency = 1000.0/N KHz
1150 N = 1000!*1000/F
1160 IF N < 2 OR N >65535! THEN PRINT"Warning! A sample rate of ";F;"
      samples/sec is outside the range of Counter 2":GOTO 1120
1170 MD% = 11 'Mode 11 to load counter
1180 D%(0) = 2 'Operate on counter #2
1190 IF N < 32767 THEN D%(1) = N ELSE D%(1) = N - 65536! 'correct for
      integer
1200 CALL DAS8 (MD%, D%(0), FLAG%)
1210 IF FLAG% <> 0 THEN PRINT "Error in loading counter 2":STOP
1220 'Pin 6 (Counter 2 Out) should now be producing the selected
      frequency.
1230 '
1240 '--Step 4: SET THE PGA PROGRAMMABLE GAIN AMPLIFIERS -----
1250 '
1260 MD% = 19
1270 GC = 0
1280 AV=1
1290 PRINT " "
1300 PRINT "      THE PROGRAMMABLE GAIN MUST BE SET ON THE AMPLIFIERS"
1310 PRINT "      ALL THE AMPLIFIERS ARE SET TO THE SAME GAIN VALUE"
1320 PRINT " "
1330 PRINT "*****"
1340 PRINT "*" "*"
1350 PRINT "* USE GAIN CODE 0 IF YOU ARE USING THE EXP-16 BOARD *"
1360 PRINT "*" "*"
1370 PRINT "*****"
1380 PRINT " "
1390 PRINT "      RANGE (VOLTS)      GAIN CODE "
1400 PRINT "      +/-5 volts      0"
1410 PRINT "      +/-10 volts     8"
1420 PRINT "      0 TO 10 volts   9"
1430 PRINT "      +/-0.5 volts    10"
1440 PRINT "      0 TO 1 volts    11"
1450 PRINT "      +/- 50 millivolts 12"
1460 PRINT "      0 TO 100 millivolts 13"
1470 PRINT "      +/- 10 millivolts 14"
1480 PRINT "      0 TO 20 millivolts 15"
1490 PRINT " "
1500 INPUT "      ENTER THE GAIN CODE : ",GC
1510 GAIN(1) = 10

```

```

1520 GAIN(9) = 20
1530 GAIN(10) = 10
1540 GAIN(11) = 1
1550 GAIN(12) = 1
1560 GAIN(13) = 100!
1570 GAIN(14) = 100!
1580 GAIN(15) = 20!
1590 GAIN(16) = 20!
1600 IF LL% < > 1 GOTO 1700
1610 PRINT " "
1620 PRINT "*****"
1630 PRINT "*"
1640 PRINT "IF THE EXP-16 UNIT IS BEING USED THEN"
1650 PRINT "THE GAIN CONTROL (100,200,1000 etc.) IS NEEDED"
1660 PRINT "*"
1670 PRINT "*****"
1680 PRINT " "
1690 INPUT "EXP-16 Gain setting (100,200,1000 etc.): ",AV
1700 PRINT " "
1710 D%(0)=GC
1720 CALL DAS8 (MD%,D%(0),FLAG%)
1730 '
1740 '----- Step 5: AVERAGING THE DATA-----
1750 '
1760 PRINT " "
1770 PRINT "DO YOU WANT AVERAGE THE DATA <Y/N>? "
1780 PRINT " "
1790 INPUT "ENTER EITHER Y OR N: ";QUES1$
1800 IF QUES1$ = "Y" OR QUES1$ = "y" THEN GOTO 2190
1810 '
1820 PRINT " "
1830 '
1840 '
1850 PRINT "THE MEMORY IS LIMIT TO 5000 TOTAL IN MODE 5"
1860 PRINT " "
1870 PRINT "DO YOU WANT TO ENTER THE TOTAL TIME"
1880 PRINT "OR THE NUMBER OF SAMPLES/CHANNEL"
1890 PRINT "USE 't' FOR TOTAL TIME OR 's' FOR TOTAL SAMPLES/CHANNEL"
1900 PRINT " "
1910 INPUT "ENTER t OR s : ";QUES2$
1920 IF QUES2$ = "T" OR QUES2$ = "t" THEN GOTO 2080
1930 PRINT " "
1940 PRINT "THE TOTAL NUMBER OF SAMPLES (ALL CHANNELS) IS 8K"
1950 PRINT " "
1960 PRINT "FOR THE EXP ACQ AND TRANSFER, THE RATE IS ABOUT 12.5 Hz"
1970 PRINT "TOTAL"
1980 PRINT "E.G., FOR 1 CHANNEL, 100 POINTS IN 8 SECONDS"
1990 PRINT "FOR 9 CHANNELS, 100 SAMPLES/CHANNEL IN 72 SECONDS OR 1.2"
2000 PRINT "MIN"
2010 PRINT " "
2020 INPUT "ENTER THE TOTAL NUMBER OF SAMPLES/CHANNEL: ",NTOT
2030 PRINT " "

```

```

2020 NT = NTOT
2030 NTOT = CHAN * NTOT
2040 NSTOP=1
2050 ' Here NTOT is change from samples/channel to the total samples
2060 GOTO 2810
2070 PRINT " "
2080 IF LL%>1 THEN INPUT " ENTER THE TOTAL TIME IN SECONDS:", TTIME
2090 IF LL%>1 THEN GOTO 2140
2100 PRINT " "
2110 PRINT "THE USE OF THE TIME MODE FOR THE EXP BOARD IS NOT
        APPROPRIATE"
2120 PRINT " "
2130 GOTO 1950
2140 NT = F*TTIME
2150 NTOT = NT*CHAN
2160 NSTOP=1
2170 GOTO 2810
2180 '
2190 PRINT " "
2200 PRINT , " DO YOU WANT TO STOP AFTER EACH AVERAGE ?"
2210 '
2220 PRINT " "
2230 INPUT " ENTER EITHER Y OR N: ";QUES4$
2240 IF QUES4$ = "Y" OR QUES4$ = "y" THEN NSTOP = 1
2250 '
2260 PRINT " "
2270 '
2280 PRINT , "ENTER THE NUMBER OF INDIVIDUAL DATA POINTS AT THE RATE
        ALREADY
2290 PRINT , " SELECTED THAT ARE TO GO INTO EACH AVERAGE
2300 '
2310 PRINT " "
2320 INPUT "ENTER THE NUMBER OF POINTS PER CHANNEL: ", NTOT
2330 ' NTOT here is being used as the points/channel
2340 IF LL%=1 THEN NTOT=NTOT ELSE NTOT = NTOT*CHAN
2350 ' Here NTOT is changed to the total samples for the PGA
2360 PRINT " "
2370 '
2380 PRINT , "DO YOU WANT TO ENTER THE TOTAL TIME OF THE RUN OR
2390 PRINT , " THE TOTAL NUMBER OF AVERAGES TO BE TAKEN
2400 PRINT " "
2410 PRINT , "USE 't' FOR TOTAL TIME OR 'a' FOR TOTAL NUMBER FOR AVERAGES
2420 PRINT " "
2430 INPUT "ENTER t OR a : ";QUES3$
2440 PRINT " "
2450 IF QUES3$ = "T" OR QUES3$ = "t" THEN GOTO 2520
2460 '
2470 INPUT "ENTER THE NUMBER OF AVERAGES (<100): ", NAVES
2480 '
2490 C=C+1
2500 GOTO 2730
2510 '

```

```

2520 C=1
2530 IF LL%>1 THEN GOTO 2590
2540 PRINT " "
2550 PRINT "THE USE OF THE TIME MODE FOR THE EXP BOARD IS NOT
      APPROPRIATE"
2560 C=0
2570 PRINT " "
2580 GOTO 2460
2590 PRINT "          FOR 8 CHANNELS AND XXX POINTS/AVERAGE"
2600 PRINT "          YYY SEC ARE NEEDED FOR DATA"
2610 PRINT "          AND ZZZ SEC ARE NEEDED FOR THE AVERAGING OF 100 POINTS"
2620 PRINT " "
2630 PRINT "          NEXT THE TOTAL TIME WILL BE ENTERED BUT NOTE"
2640 PRINT "          THE A/D CONVERSION WILL START IMMEDIATELY AFTER THE
      RETURN"
2650 PRINT " "
2660 PRINT "          IF YOU HAVE SELECTED TO STOP AFTER EACH AVERAGE"
2670 PRINT "          THE STOP TIME BETWEEN AVERAGES IS NOT ADDED IN THE RUN"
2680 PRINT " "
2690 INPUT "ENTER THE TOTAL RUN TIME IN SECONDS :",TTIME
2700 PRINT " "
2710 TOLTIME = (NTOT /F) + (.025*NTOT)
2720 NAVES = (TTIME/TOLTIME)
2730 '
2740 IF C = 1 THEN TSIN = TIMER
2750 TS(C) = TIMER - TSIN
2760 IF (LL%=1) AND (NNINIT>0) AND (NSTOP=1) THEN GOTO 2880
2770 IF (LL%=1) AND (NNINIT>0) AND (NSTOP=0) THEN GOTO 2910
2780 NNINIT=5
2790 IF LL% < > 1 GOTO 3210
2800 '
2810 '--Step 6: SET CHANNELS ON EXP-16 OR USE PGA AND ACQUIRE DATA -----
2820 '
2830 '      Next select each EXP-16 channel by MODE 14 and convert it.
2840 '
2850 IF LL% < > 1 GOTO 3210
2860 IF CEXP=1 THEN I=LM%
2870 '
2880 PRINT:COLOR 0,7:PRINT"          PRESS any key to start A/D
      conversions ";;:COLOR 7,0
2890 IF INKEY$ = "" GOTO 2890
2900 '
2910 PRINT:COLOR 0,7:PRINT"          Performing A/D conversions -
      please wait ";;:COLOR 7,0
2920 '
2930 IF CEXP=1 THEN I=LM%
2940 EXPA=LM%
2950 EXPB=UM%
2960 TSIN1=TIMER
2970 FOR SUB% = EXPA TO EXPB
2980 MD% = 14
2990 CALL DAS8 (MD%, SUB%, FLAG%)

```

```

3000 IF FLAG% <> 0 THEN PRINT "ERROR IN EXP-16 CHANNEL NUMBER" : END
3010 '
3020 MD% = 4
3030 CALL DAS8 (MD%, D%(SUB%), FLAG%)
3040 IF FLAG% <> 0 THEN PRINT "ERROR IN PERFORMING A/D CONVERSION"
3050 '
3060 NEXT SUB%
3070 '
3080 NN=NN+1
3090 NNNN=NNNN+1
3100 NTEM=NNNN*CHAN
3110 FOR J = 1 TO CHAN
3120 IF CHAN=1 THEN GOTO 3140
3130 I=J+1
3140 A%((NN-1)*CHAN+J-1) = D%(I)
3150 NEXT J
3160 IF NTEM < NTOT GOTO 2970
3170 TSIN2=TIMER
3180 TINC=(TSIN2-TSIN1)/NTOT
3190 GOTO 3350
3200 '
3210 '      Alternate Data Conversion when not using EXP-16 board
3220 '
3230 IF (NSTOP = 0) THEN GOTO 3280
3240 '
3250 PRINT:COLOR 0,7:PRINT"                PRESS any key to start A/D
      conversions ";;:COLOR 7,0
3260 IF INKEY$ = "" GOTO 3260
3270 '
3280 MD%= 5
3290 D%(0)= VARPTR(A%(0))
3300 D%(1) = NTOT
3310 CLS:COLOR 0,7:PRINT"                Performing A/D conversions -
      please wait ";;:COLOR 7,0
3320 CALL DAS8 (MD%, D%(0), FLAG%)
3330 IF FLAG% <> 0 THEN PRINT "Error in setting mode 5":STOP
3340 CLS
3350 '
3360 '----- Step 7:  AVERAGING THE DATA -----
3370 '
3380 NNNN=0
3390 IF QUES1$ = "N" OR QUES1$ = "n" GOTO 3810
3400 IF (C > 1) THEN GOTO 3500
3410 '
3420 PRINT " "
3430 PRINT "      zzz SEC ARE NEEDED FOR 100 POINT AVERAGES"
3440 PRINT " "
3450 PRINT "      THE FIRST COLUMN IS THE NUMBER OF THE AVERAGE "
3460 PRINT "      THE SECOND COLUMN IS THE TIME IN SECONDS"
3470 PRINT "      THE THIRD COLUMN IS THE VALUE OF THE VARIABLE"
3480 PRINT " "
3490 PRINT "      THERE IS A LINE FOR EACH OF THE CHANNELS USED"

```

```

3500 BEEP
3510 PRINT " "
3520 PRINT "      NOW AVERAGING DATA "
3530 PRINT " "
3540 FOR I=1 TO CHAN
3550 FOR J= 1 TO NTOT STEP CHAN
3560 NNN=J-2+I
3570 X(I,C) = X(I,C) + A%(NNN)*GAIN(GC+1)/(AV*4096)
3580 NEXT J
3590 X(I,C) = X(I,C)*CHAN/NTOT
3600 NEXT I
3610 FOR J=1 TO CHAN
3620 PRINT C,TS(C),X(J,C)
3630 PRINT " "
3640 NEXT J
3650 NN=0
3660 NNNN=0
3670 IF C< NAVES THEN GOTO 2490
3680 '
3690 'PRINT " "
3700 '
3710 INPUT "FILE NAME WITHOUT THE EXTENSION";F$
3720 O$=F$+".DAT"
3730 OPEN O$ FOR OUTPUT AS #1
3740 PRINT #1,O$
3750 FOR I = 1 TO C
3760 PRINT #1, TS(I), X(1,I), X(2,I), X(3,I), X(4,I), X(5,I), X(6,I),
      X(7,I), X(8,I), X(9,I)
3770 NEXT I
3780 CLOSE
3790 END
3800 '
3810 '--- Step 8: CHOOSE TYPE OF OUTPUT DESIRED -----
3820 '
3830 CLS : PRINT"Choose from the following:-"
3840 PRINT:PRINT" <1> - Generate a data file & plot using the DAS-8 PGA
      graphics package"
3850 PRINT:PRINT" <2> - Display data on screen"
3860 PRINT:PRINT" <3> - Exit to BASIC"
3870 PRINT:PRINT" <4> - Write and output file"
3880 PRINT " "
3890 PRINT:PRINT" Enter selection number (1-4) : ";
3900 A$= INKEY$: IF A$= "" GOTO 3900
3910 PRINT A$
3920 IF VAL(A$)=1 THEN GOTO 3980
3930 IF VAL(A$)=2 THEN GOTO 4370
3940 IF VAL(A$)=3 THEN CLS:END
3950 IF VAL(A$)=4 THEN GOTO 4660
3960 PRINT"[ ";A$;" ] is not a valid entry. Please re-enter":GOTO 3890
3970 '
3980 '--- Step: 9  GENERATE GRAPHICS FILE & PLOT -----
3990 CLS

```

```

4000 LOCATE 1,1:INPUT"DATA FILE NAME [DRIVE]:NAME.EXT";FILX$
4010 OPEN FILX$ AS #1 LEN = 30
4020 FIELD #1, 15 AS X$, 15 AS Y$
4030 '
4040 LOCATE 3,1:COLOR 0,7:PRINT"L";:COLOR 7,0:PRINT"ine, or ";:COLOR
      0,7:PRINT"D";:COLOR 7,0:PRINT"ot plot mode?"
4050 LOCATE 3,29:INPUT"",A$
4060 IF A$="L" OR A$="1" THEN M=1:GOTO 4100
4070 IF A$="D" OR A$="d" THEN M=0:GOTO 4100
4080 LOCATE 4,1:PRINT"RE-ENTER":LOCATE 3,1:PRINT SPC(79):GOTO 4040
4090 '
4100 LSET X$ = MKS$(NTOT):LSET Y$= MKS$(M)
4110 PUT #1,1
4120 '
4130 FOR I=2 TO NTOT+1
4140 LSET X$=MKS$((I-2)/F):LSET Y$=MKS$(A%(I-2)*GAIN(GC+1)/(AV*4096)
4150 PUT #1, I
4160 NEXT I
4170 '
4180 CLOSE #1
4190 '
4200 OPEN "RLINPLT.LNK" AS #1 LEN = 30
4210 FIELD #1,30 AS RLNK$
4220 LSET RLNK$ = MKI$(1)
4230 PUT #1,1
4240 CLS
4250 INPUT "Enter graph Y axis label :",Y$
4260 IF LEN(Y$)>30 THEN Y$=LEFT$(Y$,30)
4270 LSET RLNK$ = Y$ 'Y axis label
4280 INPUT "Enter graph X axis label : ",X$
4290 IF LEN(X$)>30 THEN X$=LEFT$(X$,30)
4300 PUT #1,2
4310 LSET RLNK$ = X$
4320 PUT #1,3
4330 LSET RLNK$ = FILX$
4340 PUT #1,4
4350 CLOSE #1
4360 RUN"LINPLT
4370 '
4380 '----- Display data on screen and return to menu -----
4390 '
4400 CLS
4410 PTIME=0
4420 LOCATE 25,1:PRINT"Press any key to STOP/START display,<ESC> key to
      return to data storage menu ";:LOCATE 1,1
4430 IF LL% = 1 GOTO 4500
4440 IF GC <12 GOTO 4460
4450 IF GC > 11 GOTO 4480
4460 PRINT"Time      Channel data (volts)"
4470 GOTO 4510
4480 PRINT"Time      Channel data (millivolts)"
4490 GOTO 4510

```



```

4500 PRINT "The EXP-16 is being used, all volltages are volts"
4510 FOR I = 0 TO NTOT
4520 PTIME=PTIME+TINC
4530 IF LL%>1 THEN PRINT I/F, A%(I)*GAIN(GC+1)/(AV*4096)
4540 IF LL%=1 THEN PRINT PTIME, A%(I)*GAIN(GC+1)/(AV*4096)
4550 A$ = INKEY$
4560 IF A$=CHR$(27) THEN I = NTOT+3
4570 IF A$<>" " THEN GOTO 4620
4580 NEXT I
4590 IF I =NTOT+3 GOTO 3810
4600 COLOR 0,7:PRINT" Press any key to return to data storage menu
      ";:COLOR 7,0
4610 IF INKEY$="" GOTO 4610
4620 GOTO 3810
4630 FOR K = 1 TO 50 :NEXT K      'DELAY
4640 IF INKEY$ = "" GOTO 4640
4650 INPUT " FILENAME WITHOUT EXTENSION";F$
4660 '--- Step: 10 WRITE AND OUTPUT FILE -----
4670 PTIME=0
4680 INPUT " FILENAME WITHOUT EXTENSION";F$
4690 O$ = F$ + ".DAT"
4700 OPEN O$ FOR OUTPUT AS #1
4710 PRINT #1,O$
4720 FOR I=0 TO NTOT
4730 PTIME=PTIME+TINC
4740 IF LL%>1 THEN PRINT #1, I/F, A%(I)*GAIN(GC+1)/(AV*4096)
4750 IF LL%=1 THEN PRINT #1, PTIME, A%(I)*GAIN(GC+1)/(AV*4096)
4760 NEXT I
4770 CLOSE
4780 END

```

Appendix B
Program List for Conversion

```

10 / THIS PROGRAM IS TO CONVERT THE RAW DATA TO ENGINEERING UNITS AND
20 / GENERATE AN OUTPUT FILE IN TERMS OF TEMPERATURES, FLUXES, h ETC.
25 /
26 SW1=0
30 DIM MVOL(10)
200 INPUT "INPUT FILE NAME WITHOUT EXTENTION"; F$
210 OI$ = F$ + ".DAT"
220 INPUT "OUTPUT FILE NAME WITHOUT EXTENTION"; F$
230 OO$ = F$ + ".DAT"
231 INPUT "DERIVED INFO (e.g., Nu) OUTPUT FILE NAME WITHOUT EXTENTION";
    F$
232 OD$ = F$ + ".DAT"
233 INPUT "AVERAGE INFO OUTPUT FILE NAME WITHOUT EXTENTION"; F$
234 OAV$ = F$ + ".DAT"
235 INPUT "ENTER THE NUMBER OF AVERAGES :", NTOT
240 NN = 0
250 OPEN OI$ FOR INPUT AS #1
260 OPEN OO$ FOR OUTPUT AS #2
270 OPEN OD$ FOR OUTPUT AS #3
271 OPEN OAV$ FOR OUTPUT AS #4
280 I = 2
290 INPUT #1, T, MVOL(I), MVOL(I+1), MVOL(I+2), MVOL(I+3), MVOL(I+4),
    MVOL(I+5), MVOL(I+6), MVOL(I+7), MVOL(I+8)
300 TB = -.178546 + .00440909 * MVOL(I)
310 T1 = -.178546 + .00440909 * MVOL(I + 1)
320 T2 = -.178546 + .00440909 * MVOL(I + 3)
330 TF = -.178546 + .00440909 * MVOL(I + 4)
340 VISB = .830714 - .00610637 * TB
350 VIS1 = .830714 - .00610637 * T1
360 VIS2 = .830714 - .00610637 * T2
370 VISF = .830714 - .00610637 * TF
380 CP = 4.19
390 KB = 455.2 + 6.25 * TB - (.05 * (TB ^ 2))
400 K1 = 455.2 + 6.25 * T1 - (.05 * (T1 ^ 2))
410 K2 = 455.2 + 6.25 * T2 - (.05 * (T2 ^ 2))
420 KF = 455.2 + 6.25 * TF - (.05 * (TF ^ 2))
421 KBF = KB * 3.4122 * .3048 / (273.15 * 1.8 + 32)
422 K1F = K1 * 3.4122 * .3048 / (273.15 * 1.8 + 32)
423 K2F = K2 * 3.4122 * .3048 / (273.15 * 1.8 + 32)
460 PRF = 10.9704 - .2284 * TF(K) + .0016 * (TF ^ 2)
470 DENB = .9 + (11.5845 - .0543 * TB) * .01
480 DEN1 = .9 + (11.5845 - .0543 * T1) * .01
490 DEN2 = .9 + (11.5845 - .0543 * T2) * .01
500 DENF = .9 + (11.5845 - .0543 * TF) * .01
510 QB = MVOL(I + 6) / 1.347
520 Q1 = MVOL(I + 7) / 1.347
521 Q2 = MVOL(I + 8) / 1.347
522 IF SW1>0 GOTO 532
531 INPUT "ENTER THE DIAMETER OF THE TANK(INCH) : ",DT
532 TBF = TB * 1.8 + 32
533 T1F = T1 * 1.8 + 32
534 T2F = T2 * 1.8 + 32

```

```

540 HB =QB / TBF
550 H1 = Q1 / T1F
560 H2 = Q2 / T2F
561 NUB = HB *DT * (1 / 12) / KBF
562 NU1 = H1 *DT * (1 / 12) / K1F
563 NU2 = H2 *DT * (1 / 12) / K2F
564 IF SW1>0 GOTO 600
570 INPUT "ENTER THE DIAMETER OF THE IMPELLER(INCH) : ", D
580 INPUT "ENTER THE R.P.M OF AGITATOR : ", RPM
590 N = RPM / 60
591 SW1=1
600 RE = ((D * 2.54) ^ 2) * N * DENF / (VISF * 10)
610 KC2 = .74
620 A = 2 / 3
630 B = 1 / 3
640 C = .14
641 TWB = TF - TB
642 TW1 = TF - T1
643 TW2 = TF - T2
645 VISWB = .830714 - .00610637# * TWB
646 VISW1 = .830714 - .00610637# * TW1
647 VISW2 = .830714 - .00610637# * TW2
650 NUCB = KC2 * (RE ^ A) * (PR ^ B) * (VISF / VISWB)
660 NUC1 = KC2 * (RE ^ A) * (PR ^ B) * (VISF / VISW1)
670 NUC2= KC2 * (RE ^ A) * (PR ^ B) * (VISF / VISW2)
680 HCB = NUCB * KBF / (DT / 12)
690 HC1 = NUC1 * K1F / (DT / 12)
700 HC2 = NUC2 * K2F / (DT / 12)
715 PRINT #2,T,TB,T1,T2,TF,QB,Q1,Q2,HB,H1,H2
730 PRINT #3,T,NUB,NU1,NU2,NUCB,NUC1,NUC2,HCB,HC1,HC2
750 SUMTB = SUMTB + TB
760 SUMT1 = SUMT1 + T1
770 SUMT2 = SUMT2 + T2
780 SUMTF = SUMTF + TF
790 SUMQB = SUMQB + QB
800 SUMQ1 = SUMQ1 + Q1
810 SUMQ2 = SUMQ2 + Q2
820 SUMHB = SUMHB + HB
830 SUMH1 = SUMH1 + H1
840 SUMH2 = SUMH2 + H2
850 SUMNUB = SUMNUB + NUB
860 SUMNU1 = SUMNU1 + NU1
870 SUMNU2 = SUMNU2 + NU2
880 SUMNUCB = SUMNUCB + NUCB
890 SUMNUC1 = SUMNUC1 + NUC1
900 SUMNUC2 = SUMNUC2 + NUC2
910 SUMHCB = SUMHCB + HCB
920 SUMHC1 = SUMHC1 + HC1
930 SUMHC2 = SUMHC2 + HC2
1130 NN=NN+1
1140 IF NN<NTOT THEN GOTO 290
1145 CLOSE #2

```

```

1145 CLOSE #3
1150 AVTB = SUMTB / NTOT
1160 AVT1 = SUMT1 / NTOT
1170 AVT2 = SUMT2 / NTOT
1180 AVTF = SUMTF / NTOT
1190 AVQB = SUMQB / NTOT
1200 AVQ1 = SUMQ1 / NTOT
1210 AVQ2 = SUMQ2 / NTOT
1220 AVHB = SUMHB / NTOT
1230 AVH1 = SUMH1 / NTOT
1240 AVH2 = SUMH2 / NTOT
1250 AVNUB = SUMNUB / NTOT
1260 AVNU1 = SUMNU1 / NTOT
1270 AVNU2 = SUMNU2 / NTOT
1280 AVNUCB = SUMNUCB / NTOT
1290 AVNUC1 = SUMNUC1 / NTOT
1300 AVNUC2 = SUMNUC2 / NTOT
1310 AVHCB = SUMHCB / NTOT
1320 AVHC1 = SUMHC1 / NTOT
1330 AVHC2 = SUMHC2 / NTOT
1331 OPEN OO$ FOR INPUT AS #2
1332 NN=0
1333 INPUT #2,T,TB,T1,T2,TF,QB,Q1,Q2,HB,H1,H2
1334 SUMTBS= SUMTBS+(TB - AVTB)^2
1335 SUMT1S= SUMT1S+(T1 - AVT1)^2
1336 SUMT2S= SUMT2S+(T2 - AVT2)^2
1337 SUMTFS= SUMTFS+(TF - AVTF)^2
1338 SUMQBS= SUMQBS+(QB - AVQB)^2
1339 SUMQ1S= SUMQ1S+(Q1 - AVQ1)^2
1400 SUMQ2S= SUMQ2S+(Q2 - AVQ2)^2
1410 SUMHBS= SUMHBS+(HB - AVHB)^2
1420 SUMH1S= SUMH1S+(H1 - AVH1)^2
1430 SUMH2S= SUMH2S+(H2 - AVH2)^2
1430 NN=NN+1
1440 IF NN<NTOT THEN GOTO 1333
1450 AVTBS = SUMTBS/NTOT
1460 AVT1S = SUMT1S/ NTOT
1470 AVT2S = SUMT2S/ NTOT
1480 AVTFS = SUMTFS/ NTOT
1490 AVQBS = SUMQBS/ NTOT
1500 AVQ1S= SUMQ1S/ NTOT
1510 AVQ2S= SUMQ2S/ NTOT
1520 AVHBS= SUMHBS/ NTOT
1530 AVH1S= SUMH1S/ NTOT
1540 AVH2S= SUMH2S/ NTOT
1541 NN=0
1560 OPEN OD$ FOR INPUT AS #3
1570 INPUT #3,T,NUB,NU1,NU2,NUCB,NUC1,NUC2,HCB,HC1,HC2
1580 SUMNUBS= SUMNUBS+(NUB - AVNUB)^2
1590 SUMNU1S= SUMNU1S+(NU1 - AVNU1)^2
1600 SUMNU2S= SUMNU2S+(NU2 - AVNU2)^2
1610 SUMNUCBS= SUMNUCBS+(NUCB - AVNUCB)^2

```

```
1620 SUMNUC1S= SUMNUC1S+(NUC1 - AVNUC1)^2
1630 SUMNUC2S= SUMNUC2S+(NUC2 - AVNUC2)^2
1640 SUMHCBS= SUMHCBS+(HCB - AVHCB)^2
1650 SUMHC1S= SUMHC1S+(HC1 - AVHC1)^2
1660 SUMHC2S= SUMHC2S+(HC2 - AVHC2)^2
1670 NN=NN+1
1680 IF NN<NTOT THEN GOTO 1570
1700 AVNUBS= SUMNUBS/ NTOT
1710 AVNU1S= SUMNU1S/ NTOT
1720 AVNU2S= SUMNU2S/ NTOT
1730 AVNUCBS= SUMNUCBS/ NTOT
1740 AVNUC1S= SUMNUC1S/ NTOT
1750 AVNUC2S= SUMNUC2S/ NTOT
1760 AVHCBS= SUMHCBS/ NTOT
1770 AVHC1S= SUMHC1S/ NTOT
1780 AVHC2S= SUMHC2S/ NTOT
1790 INPUT #4,AVTB,AVT1,AVT2,AVTF,AVQB,AVQ1,AVQ2,AVHB,AVH1,AVH2
1800 INPUT #4,AVNUB,AVNU1,AVNU2,AVNUCB,AVNUC1,AVNUC2,AVHCB,AVHC1,AVHC2
1810 INPUT #4, AVTBS, AVT1S, AVT2S, AVTFS, AVQBS, AVQ1S, AVQ2S, AVHBS,
    AVH1S, AVH2S
1820 INPUT #4, AVNUBS, AVNU1S, AVNU2S, AVNUCBS, AVNUC1S, AVNUC2S,
    AVHCBS, AVHC1S, AVHC2S
1830 CLOSE #4
1840 END
```

```
1620 SUMNUC1S= SUMNUC1S+(NUC1 - AVNUC1)^2
1630 SUMNUC2S= SUMNUC2S+(NUC2 - AVNUC2)^2
1640 SUMHCBs= SUMHCBs+(HCB - AVHCB)^2
1650 SUMHC1S= SUMHC1S+(HC1 - AVHC1)^2
1660 SUMHC2S= SUMHC2S+(HC2 - AVHC2)^2
1670 NN=NN+1
1680 IF NN<NTOT THEN GOTO 1570
1700 AVNUBS= SUMNUBS/ NTOT
1710 AVNU1S= SUMNU1S/ NTOT
1720 AVNU2S= SUMNU2S/ NTOT
1730 AVNUCBS= SUMNUCBS/ NTOT
1740 AVNUC1S= SUMNUC1S/ NTOT
1750 AVNUC2S= SUMNUC2S/ NTOT
1760 AVHCBs= SUMHCBs/ NTOT
1770 AVHC1S= SUMHC1S/ NTOT
1780 AVHC2S= SUMHC2S/ NTOT
1790 INPUT #4,AVTB,AVT1,AVT2,AVTF,AVQB,AVQ1,AVQ2,AVHB,AVH1,AVH2
1800 INPUT #4,AVNUB,AVNU1,AVNU2,AVNUCB,AVNUC1,AVNUC2,AVHCB,AVHC1,AVHC2
1810 INPUT #4, AVTBS, AVT1S, AVT2S, AVTFS, AVQBS, AVQ1S, AVQ2S, AVHBS,
    AVH1S, AVH2S
1820 INPUT #4, AVNUBS, AVNU1S, AVNU2S, AVNUCBS, AVNUC1S, AVNUC2S,
    AVHCBs, AVHC1S, AVHC2S
1830 CLOSE #4
1840 END
```