Paper Engineering Senior Theses   Chemical and Paper Engineering

4-1974

Investigation of the Static Mixer for Improved Heat Transfer to Black Liquors

Bruce J. Redmond
Western Michigan University

Recommended Citation

Redmond, Bruce J., "Investigation of the Static Mixer for Improved Heat Transfer to Black Liquors" (1974). *Paper Engineering Senior Theses*. 405.
https://scholarworks.wmich.edu/engineer-senior-theses/405

INVESTIGATION OF THE

STATIC MIXER FOR IMPROVED

HEAT TRANSFER TO BLACK LIQUORS

by

BRUCE J. REDMOND

A Thesis submitted to

Mr. John Fisher

in partial fulfillment

of the

Degree of Bachelor of Science

Western Michigan University

Kalamazoo, Michigan

April 1974

ABSTRACT

The objective of this experiment was to determine an improved

method by which evaporation of kraft black liquors to the 50 to

65% total solids level could be sufficiently performed in multiple

effect evaporators. This would eliminate the need of the highly

malordorous direct contact evaporators which are presently used.

Heat transfer characteristics of the Kenics Static Mixer were

examined to determine if its application in multiple effect

evaporator tubes would possibly reduce viscous liquor film layers

which now hinder heat transfer. A single pass heat exchange unit

that allowed removal of the inner tube and its replacement by a

Static Mixer unit was designed and built. Heat and mass balances

were performed on the unit to determine possible gains in heat

transfer achieved using the Static Mixer. Experimentation done

in the laminar regions of flow showed that the inside film

coefficient was enhanced a slight, but significant amount. It is

recommended that further study be made at higher liquor concen-

trations and at turbulent flow conditions.

TABLE OF CONTENTS

FIGURES

LITERATURE REVIEW

The making of pulp and paper has come a long way since T'sai

Lun first made his sheets of meshed mulberry fibers in 105 A.D..

As an example of the growth in this industry, the consumption of

paper per capita during 1969 in the United States reached 576 pounds.

It was not until the middle of the nineteenth century that

wood was used as a raw material in making paper by the major pulping

processes. The first chemical wood-pulp mills for both the alkaline and

acid pulping processes were started between 1852 and 1874.[1] In

the past 100 years, great technical progress has been made in the

manufacture of pulp and paper products. The range of wood species

used as a raw material has required many technical modifications to

the various pulping processes. In growing to the huge proportions

that have now been obtained, the pulp and paper industry has come

face to face with numerous dilemmas that must be dealt with.

In his report to International Paper Company's annual meeting,

Paul A. Gorman, chairman, president, and chief executive of IPC,

made an assessment of today's major problems.[2] Two areas of his

report included the energy "crisis" and the economics of environ-

mental control. Mr. Gorman states that recent and past increases

in fuel costs have considerably outstripped increases in other

elements of cost. On the environment, he notes that the nation's

pulp and paper companies have spent over $1 billion for environ-

mental controls and another $1 billion in outlays is planned. Mr.

Gorman agrees that further degradation to our land must stop, but

before we spend such vast resources, the industry should spend at

least a small portion to determine once and for all what the real

dangers are to our environment, and what the best ways are to sta-

bilize our environment below those danger points.

Mr. Gorman states: "We are continually searching for methods

to reduce the amount of energy required to produce a ton of finished

product by recovering heat which is not now utilized and by install-

ing equipment or using processes which require less energy per ton

of product."

The possible revamping of present pulping processes to protect the environment is the main topic of this paper. More precisely, it deals with the evaporation of spent liquors in the kraft pulping process.

A necessary stage in the recovery of cooking liquors in the kraft process is the evaporation of black liquor from the digestion and washing stages. If the black liquor were discarded from the process after washing the pulp, it would be necessary to replace all the alkali charged to the digesters and the cost of alkaline pulp would be prohibitive. Hence, economy dictates the recovery of the alkali as completely as possible, and the first step in this procedure is to concentrate the weak black liquor to the density required by the recovery furnace. This necessitates the evaporation of all the black liquor from an original concentration of about 14 to 18% total solids to between 45 and 70% total solids, depending on the type of recovery unit used. For the higher concentrations, the liquor leaves the initial evaporation stage at approximately 50% and further evaporization is generally carried out in a direct

contact evaporator.

In the direct contact evaporator the liquor and flue gas from the recovery boiler are brought into intimate physical contact, and there is a mass transfer of water vapor from the liquor to the gas across the liquor-gas interface. The design of the direct contact evaporator requires that adequate liquor surface be provided for the desired heat and mass transfer. If liquor is splashed or sprayed on hot metal, the quantity must be sufficient for continuous washing. A further reason for continuous agitation or movement of the liquor is that sludge tends to precipitate because of acidification by absorption of CO_2 and SO_2 which decreases solubility of the dissolved solids.[1]

One of the chief drawbacks concerning the use of contact evaporators is the fact that they have usually been malodorous. Elimination of the direct contact evaporator in the recovery boiler design removes a prime source of odor associated with the kraft process. Where a contact evaporator is used, odor can be reduced

by oxidation of sulfur compounds in the liquor before entering.

The oxidation operation stabilizes sulfide compounds to preclude

their reaction in the evaporator with flue gas and consequent re-

lease of volatile odor compounds. Oxidation can effectively reduce

but does not eliminate discharge of malodorous gas compounds from

the direct contact evaporator.

One mill practicing the process of black liquor oxidation is

Union Camp's Savannah, Georgia mill. In their process, hydrogen

 sulfide generation in the direct contact evaporators will be elim-

inated by a heavy black liquor oxidation system using air spargers.

Liquor will be fed at 225° F and 50% solids to a two-stage oxidation

system designed for a maximum flowrate of 900 gpm. Each oxidizer

will be 35 feet in diameter and 40 feet high and the air supply

will be provided by a 12,000-scfm compressor. An intermediate soap

separator will be located between the two stages. This system is

capable of oxidizing up to 99% of the sodium sulfide.[3]

The cost of these added oxidation systems and the contact

evaporators themselves runs into many thousands of dollars. Power

consumption is great due to the needs of the added machinery.

As was noted earlier, the direct contact evaporator can be

eliminated and final liquor concentrating can be completed in the

multiple effect evaporator.

The initial evaporating system consists of a number of effects

comprised of numerous tubular channels heated by steam on the outside.

The complete tube bundle, which refers to the side-by-side position-

ing of the tubes, is enclosed in a shell in which the steam circulates.

In all heat transfer equipment, such as evaporators, heaters,

and condensers, it is usually necessary to transfer heat from one

fluid through a metal wall to another fluid. In most cases the heating

medium is steam, the heating surface is in the form of metal tubes,

and the material heated is a liquid. In this case, the heated

material is black liquor. The flow of heat under these conditions

is controlled by three factors: 1) the area of the heating surface,

2) the total working temperature drop, and 3) the overall coefficient

of heat transfer.[4]

If q is the rate of heat transfer in BTU/hour, Q is the total

heat transfer after $\emptyset$ hours, A is the area of the heating surface

in square feet, Δt is the total temperature drop across the heating

surface in degrees Fahrenheit, and U is the overall coefficient of

heat transfer in BTU/ft^2 of heating surface/ degrees Fahrenheit

temperature drop/hour, the fundamental equation of heat transfer is

$$\frac{Q}{\emptyset} = q = UA\Delta t$$

The flow of heat in clean tubes will meet a minimum of three separate

resistances in series: 1) the condensate film resistance between the

steam and the metal wall, 2) the resistance of the metal itself, and

3) the liquor film resistance between the metal wall and the flowing liquor.

In practically every evaporator, the most important, and by far the

controlling factor in the rate of heat transfer, is the condition

at the liquor side of the tubes, or the "liquor film coefficient."

For heat transfer operations required in the processing of highly

viscous materials, the inside film resistance is so high that other

resistances are negligible. In these cases the overall heat transfer
coefficient is approximately equal to the inside film coefficient.

The liquor film coefficient is controlled by the thickness of
the stagnant film of liquor on the surface of the metal, which, in
the final analysis, is determined by two factors: 1) the viscosity
of the liquor at the prevailing concentration and temperature and
2) the turbulence or velocity of the liquor at the wall of the tube.
The higher the concentration and the lower the temperature of the
liquor, the greater will be the viscosity and the lower will be the
rate of heat transfer in the evaporator; similarly, the lower the rate
of the circulation, the lower will be the rate of heat transfer.

Fouling on the inside of the tubes must be taken into con-
sideration when calculations of overall coefficients of heat transfer
are made. The metal tube surface may become coated with organic scale
or some other deposit which may reduce the rate of heat transfer
far below that normally obtained. Such a condition of scale, be-
cause of the low conductivity of the scale material, greatly increases resistance

to the flow of heat through the tube.

In some cases there is a tendency toward formation of a coating of organic matter on the surface of the evaporator tubes. This is usually a result of a slow polymerization and carbonization during the destructive-distillation reaction, which occurs on heating in the presence of caustic soda. This sort of deposit is a gummy, black, carbonaceous material which greatly reduces the rate of heat transfer. It can usually be removed by boiling out the evaporator with water, but it is sometimes necessary to boil with a weak alkali wash or a soda ash or white-liquor solution. In rare cases, it is difficult to remove the deposit by boiling out, and means of mechanical removal may be necessary. This cleaning is both difficult and expensive. This is seldom serious in low temperature operations at concentrations below 50% total solids.

Whenever possible, evaporator tubes are made of cast iron and steel. Many solutions however, attack ferrous metals, or are contaminated by them. Special materials such as copper, nickel,

stainless steel, aluminum, impervious graphite, and lead are then

used. Since these materials are expensive, high heat transfer rates

become especially desirable to minimize the first cost of the

equipment.

E. H. Backteman and R. Y. Marr have written an article describ-

ing work done for Scandinavian mills in which they state that weak

black liquor from the kraft pulping process can and should be con-

centrated to the 50 - 65% total solids level in the multiple effect

evaporator.[6] There are two benefits from handling the black

liquor this way. One is that it improves heat economy and the sec-

ond is that no direct contact evaporator is needed, and thus, no

H_2S is released to the flue gas.

The main objection to the modern system has been, and still

is, the problems involved in operating a multiple effect evaporator

at high concentrations of the heavy black liquor. One of the biggest

problems encountered was that of fouling on the liquor side of the

tubes due to the increased viscosity and concentration of the liquor.

The problems encountered due to fouling have been reduced by in-

corporating a unique piping arrangement among the effects. Even

with this arrangement it is necessary to carry out a complete boil-

out, with weak black liquor or water, of the final stages of the

evaporator. This washing takes about two hours once or twice a

week.

In light of the above discussion, it would seem reasonable

that in order to increase heat transfer in a black liquor evaporator,

a more efficient means of getting heat through the liquor film layer

and spread throughout the liquor itself would be needed. This

could reduce initial expenditures on evaporator construction, such

as reducing elaborate piping systems as those in the Scandinavian

mills. It could also reduce required steam quantities and cost, and

give a more uniform product.

In an article by D. A. Pattison, assistant editor of Chemical

Engineering magazine, the principles and applications of motionless

inline mixers are described.[7] The improvements in heat transfer

rendered by these mixers are the main areas of interest to this project.

Three companies have come up with these units, but the mixer

made by Kenics Corporation of Danvers, Mass. is extremely simple

and inexpensive. When applied in certain evaporator areas, such

as in line with the tubular channels, evaporator performance may

be enhanced by increasing the overall heat transfer coefficient which

is presently limited by the viscous liquor film at the higher con-

centration of total solids.

The Static Mixer is an in line, no-moving part, continuous mixing

and processing unit which has no external power requirements. The

unit is constructed of a number of short elements of right- and left-

hand helices. These elements are alternated and oriented so that

each leading edge is at 90° to the trailing edge of the one ahead.

In general, the length of the individual element is approximately

1.5 diameters. The element assembly is then enclosed within a

tubular housing.[8]

Following are examples of the individual elements that are

enclosed in the unit:

Right-hand element   Left-hand element

Figure 1: Static Mixer Elements

The unit can be constructed of various materials, including: carbon

steels, stainless steels, alloy metals, exotic alloys, glass, fiber-

glass, PVC, and other plastics. The unique plug flow mix progression

within the Static Mixer unit is predictable and programmable. Careful

control of in line processing is assured in numerous blending, disp-

ersion, and thermal control applications. The radial mixing action

thermally homogenizes processed materials regardless of viscosity.

The plug flow temperature and velocity profile narrows residence

time distribution and enhances thermal history control.

Principles of operation of the Static Mixer are outlined in the

following discussion.

When the materials to be mixed are passed through the mixer,

two unique mixing actions, flow division and radial mixing, operate

simultaneously in the unit, resulting in nearly plug flow characteristics.[9]

(1) Flow Division: At the leading edge of each element the flow

divides and follows the semi-circular channel created by the element's

shape. At each succeeding element, the two flows are further divided,

resulting in an exponential progression of flow division. The pro-

gression is described by the formula

$$S = 2^n$$

where S is the number of striations produced and n is the number of

elements in the unit.

(2) Radial Mixing: In either laminar or turbulent flow, rota-

tional circulation of a processed material around the hydraulic

center of each semi-circular channel causes radial mixing of the mat-

erial, thus forcing the material from the diameter to the outer wall

of the channel. At the same time, the flow reverses its rotation at

each element junction due to the alternate right and left-hand align-

ment of the elements. Fluid rotation in a given element is opposite

the rotational hand of that element. The overall effect of radial

mixing is to cause the stream to be continuously and completely in-

verted radially so that particles entering at the center of the

stream are forced to the outer wall and back again on a continuous

basis. Because of thorough radial mixing, the radial gradients in

temperature, velocity, and composition are virtually eliminated.

Careful control over in line processing is assured in numerous blend-

ing, dispersion, and heat transfer applications.

Clockwise Rotation   Interface   Counter Clockwise Rotation
  Left-hand element   Right-hand element
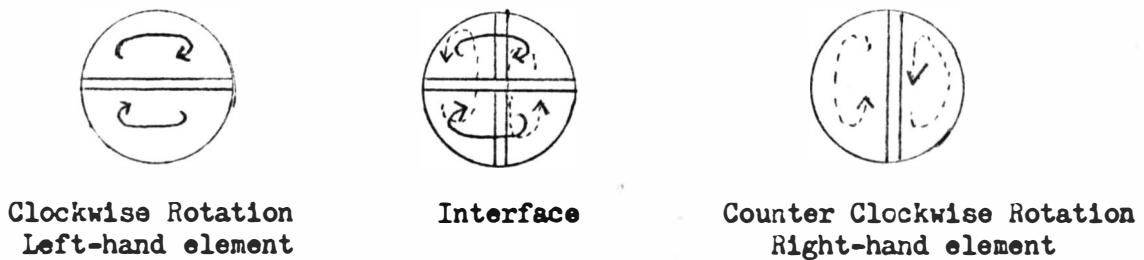
Figure 2: Radial Mixing Action of the Static Mixer

It has been shown that the use of direct contact evaporators

in the final concentration of black liquors is not advantageous due

to the odor emitted. The odor can be controlled to a certain extent,

but requires vast sums of capital costs to build the necessary aux-

iliary equipment. It appears that final concentrating in the

multiple effect evaporators themselves is currently the most prom-

ising technique.

It is the objective of this paper to show the feasability of

replacing various evaporator tubes with Static Mixer units in order

to enhance evaporator performance. The flow division and radial
mixing properties may reduce the liquor film resistance which
hinders heat transfer. There should be a reduced stagnant film
layer of liquor on the surface of the metal. Also, the forming
of scale or other deposits that deter heat transfer may be reduced.
Assuming this is true, problems now hindering thick liquor con-
centration in the multiple effect evaporators will be reduced,
making this technique more desirable.

The Static Mixer concept is relatively new and there is skep-
ticism concerning it. But in these days when energy is of such
great concern, new ideas must be worked with and utilized. Less required
mill area due to the elimination of the direct contact evaporators
and fewer shutdowns due to fouling on the inside of the evaporator
tubes would enhance the economy of the pulping process. Savings
that would be gained in operating costs could be applied to in-
crease the development of our pollution abatement programs.

EXPERIMENTAL SECTION

Equipment and Liquor Considerations

In order to carry out this study of possible heat transfer improvements caused by the Static Mixer unit, a heat exchanger was needed that would allow removal of the inner tube through which the liquor was to flow and its replacement with the Static Mixer. After searching through the Paper Science and Engineering and the Mechanical Engineering Departments of Western Michigan University, no heat exchanger fulfilling the above requirements could be found. Thus, a heat exchanger unit had to be designed and built. The photograph of Figure 3 and the schematic diagram in Figure 4 outline details of design.

Spent liquor from the softwood kraft pulping process was obtained from Mosinee Paper Corporation, Mosinee, Wisconsin. Concentration determinations were performed and it was found that the total solids concentration of the liquor was approximately 56%.

Experimental Conditions

In order to perform mass and heat balances of the unit, input

Figure 3: Photograph of Heat Exchanger
Used in This Experiment

STEAM SUPPLY INDICATOR (PSIG)
$[T_{ha}] = [T_{hb}]$

DIAL THERMOMETER
$[T_{cb}]$

LIQUOR OUT

LIQUOR FEED

REPLACEABLE INNER TUBE

STEAM TRAP

CONDENSATE

MOTOR

PUMP INPUT
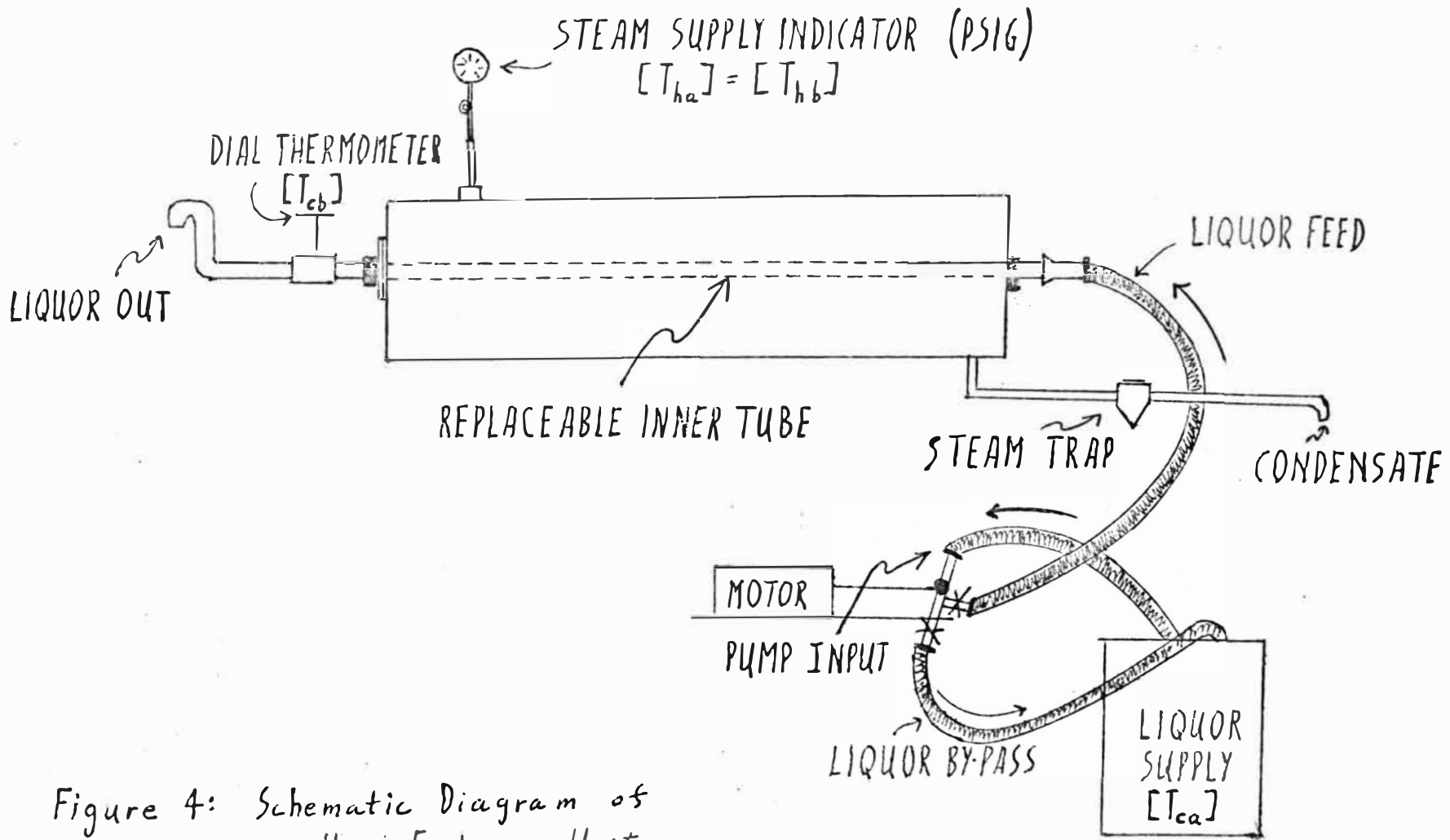
LIQUOR BY-PASS

LIQUOR
SUPPLY
$[T_{ca}]$

Figure 4: Schematic Diagram of
Heat Exchange Unit

and output temperatures of the liquor, T_{ca} and T_{cb}, were recorded.

Temperature of the condensing vapor, T_{hb}, was assumed to be equal

to input steam temperature, T_{ha}. Liquor flow rate through the unit

was controlled by a centrifugal pump equipped with a by-pass flow

line for greater flow stability. Liquor flow was held low due to

problems encountered in recording data at high flow rates. These

problems included variances using a stop watch and graduated

cylinder for flow rate determinations and time lags resulting

from the thermometers stabilizing at changing temperatures.

Data were obtained by varying liquor flow rates and in-

creasing initial liquor temperatures. The increasing initial

liquor temperatures, however, were not considered in the analysis

since relative data were taken for both the Static Mixer operation

and the empty tube operation.

Liquor concentrations were determined by placing approximately

10 millimeters of liquor in a three inch evaporating dish, weighing,

drying in a ventilated oven at 170° F for 24 hours, and reweighing.

The difference was the water content of the liquor. Data is

presented in Table III.

Observations

It was desired to run these trials with the liquor as viscous

as possible for greater enhancment of heat transfer. However, it

was necessary to heat the liquor to approximately 90°F in order to

maintain a constant pumping action. At this temperature the

viscosity of the liquor was approximately 500 centipoises. The

viscosity was noticeably decreased upon exit from the heat exchanger,

so a mean temperature based upon T_{ca} and T_{cb} was used for cal-

culation purposes.

Data Analysis

An evaluation of overall heat transfer between the two tubes

could only be determined by calculations based on heat and mass

balances. Following are the basic equations used, their meaning,

and methods involved in their determination:

1) Heat Transfer Rate, q:

$$q = \dot{m}C_p\Delta T$$

where $\dot{m}$ = mass flow rate (lbs/hr)

C_p = specific heat (BTU/lb-°F)

$\Delta T = T_{cb} - T_{ca}$ (°F)

q = heat transfer rate (BTU/hr)

This equation was used in determining the actual rate at which heat was obtained by the black liquor. Mass flow rate was obtained by first calculating the volumetric flow rate of the black liquor. Data in ml/sec was converted to ft^3/hr. This value was then multiplied by the density of the liquor at its mean temperature to get lbs/hr. Specific gravity, and thus, density, were obtained from graphs presented in Reference 4. Specific heat at the mean temperature was obtained from appropriate graphs found in Reference 10.

2) Overall Heat Transfer Coefficient, U_o :

$$U_o = q/A_o\Delta\overline{T}_L$$

where U_o = local overall heat transfer co-

efficient based on the outside

area of the inner tube $(BTU/(ft^2)(hr)(°F))$

q = heat transfer rate (BTU/hr)

A_0 = outside area of inner tube (ft^2)

$\Delta \bar{T}_L$ = logarithmic temperature difference(mean)

between input and output temperatures

of the liquor and steam.

$\Delta \bar{T}_L$ was calculated from the following equation:

$$\frac{\Delta T_1 - \Delta T_2}{\ln (\Delta T_1 / \Delta T_2)} \qquad \text{where } \Delta T_1 = T_{ha} - T_{ca}$$

$$\Delta T_2 = T_{hb} - T_{cb}$$

3) Inside Film Coefficient, h_i :

$$\frac{1}{U_o} \qquad \frac{D_o}{D_i h_i} + \frac{x_w}{K_m} \frac{D_o}{D_i} + \frac{1}{h_o}$$

where U_o = Overall heat transfer coefficient

$(BTU/(ft^2)(hr)(°F)$

D_o = outside diameter of inner tube(ft)

D_1 = inside diameter of inner tube(ft)

x_w = thickness of metal wall (ft)

k_m = thermal conductivity of metal walls

$(BTU/ (ft^2)(hr)(^{\circ}F)$

$\bar{D}_L$ = logarithmic diameter of inner tube(ft) (mean)

h_i = inside film coefficient $(BTU/(ft^2)(hr)(^{\circ}F))$

h_o = surface heat transfer coefficient for outside of tube (A value of 2000 $BTU/(ft^2)(hr)(^{\circ}F)$ was assumed for these calculations.

This equation suggests that the reciprocal of an overall co-efficient can be considered to be an overall resistance com-posed of three resistances in series. The individual terms on the right-hand side of the equation represent the individual resistances of the two fluids and of the metal wall.

4) Reynolds Number, N_{RE} :

$$N_{RE} = \frac{D_i \bar{V} \varrho}{\mu}$$

where D_i = inside diameter of the tube (ft)

$\bar{V}$ = lineal liquor velocity(ft/sec)

ϱ = density of liquor at mean temp(lb/ft^3)

$$\mu = \text{viscosity of liquor at mean}$$

$$\text{temp. (lb/ft-sec)}$$

The Reynolds number coordinates the factors that determine

the point at which a laminar boundary layer first shows

turbulence. For these calculations, viscosity was taken from

an appropriate nomograph coordinating values of liquor temp-

erature, liquor concentration, and viscosity.

5) Nusselt Number, N_u :

$$N_u = \frac{h_i D_i}{k_m}$$

where h_i = inside film coefficient

D_i = inside diameter of tube

k_m = thermal conductivity of metal

used.

The Nusselt number is the ratio of the temperature gradient

at the metal wall to the average temperature gradient across

the entire pipe.

Raw data are presented on the following pages, as is calculated

data. These can be found in Tables I and II respectively.

Graphing of results can be found in Figures 5, 6, and 7.

Discussion of Results

As can be seen from Figures 5 and 6, heat transfer rates do

increase with increasing flow rates. This is so since an increasing

amount of liquor is being heated. The leveling at higher flow

rates is due to the decreasing temperature difference since less

time is allowed for heat transfer. As noticed in the graphs, it

appears that there is no significant difference developed when

switching tubes. These plots are equivalent since the thermal con-

ductivities of the tube walls were not taken into consideration.

In full scale heat transfer operations, the thermal conductivity of

the metal walls has a negligible effect on the rate of heat transfer.

However, in my operation, the Static Mixer was encased in a stain-

less steel, type 316, casing and the empty tube was made of mild

steel. The thermal conductivity of stainless steel is 9.4 BTU/(ft)(hr)(^{o}F)

Table I: Raw Heat and Mass Balance Data STATIC MIXER UNIT

Reading#	Steam-side Balance			Liquor-side Balance			
	Time (sec)	ml	Pressure (psig)	Time (sec)	ml	T_{ca} (°F)	T_{sh} (°F)
1	15.5	34	11.0	12	94	90	180
2	15.5	34	10.7	8.0	75	93	176
3	14.7	45	10.7	5.3	90	93	148
4	14.7	45	10.6	4.1	88	93	151
5	9.9	20	11.0	9.3	47	122	190
6	9.9	20	11.0	4.5	35	124	190
7	9.9	20	10.9	7.0	62	124	171
8	9.9	29	10.9	1.9	130	124	170
9	10.0	22	10.9	5.4	45	124	200
10	10.0	22	10.9	3.8	93	145	181
11	9.9	20	10.9	3.9	70	145	179
12	9.9	25	10.9	2.4	132	145	183
13	9.9	25	10.9	1.7	130	154	181

Table I: (Cont.) Raw Heat and Mass Balance Data   EMPTY PIPE

Reading#	Steam-side Balance			Liquor-side Balance			
	Time (sec)	ml	Pressure (psig)	Time (sec)	ml	T_{ca} (°F)	T_{cb} (°F)
1	14.8	31	11.2	6.3	45	92	191
2	14.8	31	10.8	7.7	62	92	175
3	23.3	55	10.8	6.7	60	95	154
4	23.3	55	10.5	5.7	70	95	154
5	14.8	30	10.5	5.1	62	95	155
6	14.8	30	10.5	4.8	80	100	152
7	23.8	39	10.8	9.4	45	122	189
8	14.8	30	10.8	3.9	105	122	148
9	16.4	39	10.8	3.3	90	122	166
10	13.7	39	10.8	4.2	115	138	194
11	19.2	35	10.8	3.7	70	138	180
12	13.0	27	10.8	3.2	83	135	179
13	13.0	27	10.8	3.5	84	135	175

Table II: Calculated Heat and Mass Balance Data <u>STATIC MIXER UNIT</u>

$\bar{V}_{vol}$ (ft^3/hr)	q_{steam} (BTU/hr)	q_{liquor} (BTU/hr)	U (BTU/(ft^2)(hr)(^{o}F))	h_1 (BTU/(ft^2)(hr)(^{o}F))	N_{RE}	N_u
0.641	14,434	2,530	40.2	99.4	3.66	0.92
0.995	15,670	5,180	66.3	171	3.51	1.59
0.996	14,434	3,810	61.1	154	5.56	1.43
1.057	15,716	4,625	81.9	225	6.45	2.09
1.120	14,434	3,080	43.0	107	5.44	0.99
1.190	15,670	5,650	71.6	191	4.20	1.77
2.152	15,682	6,780	72.1	193	5.35	1.79
2.280	14,434	4,400	73.5	197	14.0	1.83
2.725	15,682	9,020	99.7	287	7.51	2.67
3.100	15,716	6,460	107.7	318	19.83	2.95
6.980	18,043	14,980	251.8	1272	42.8	11.8
8.700	20,926	23,400	324.2	2565	42.3	23.8
9.710	18,043	14,980	263.3	1410	65.4	13.1

Table II: (Cont.) Calculated Heat and Mass Balance Data   EMPTY PIPE

V_{vol} (ft^3/hr)	q_{steam} (BTU/hr)	q_{liquor} (BTU/hr)	U_o ($BTU/(ft^2)(hr)(^{o}F)$)	h_i ($BTU/(ft^2)(hr)(^{o}F)$)	N_{RE}	N_u
0.607	11,720	2,370	37.5	88	3.00	0.30
0.905	14,977	5,170	72.2	176	3.75	0.59
1.023	14,977	4,900	61.4	148	3.68	0.50
1.137	16,879	3,820	42.7	101	3.14	0.34
1.543	14,499	5,260	59.7	147	8.23	0.49
1.560	16,879	5,220	58.8	141	4.07	0.47
2.115	14,499	6,260	71.2	174	11.70	0.58
2.400	13,036	5,800	92.7	232	14.06	0.77
3.050	14,853	7,000	106.1	270	16.25	0.91
3.290	14,853	8,325	129.9	341	18.32	1.14
3.420	14,499	5,110	61.9	150	12.99	0.50
3.470	17,008	8,720	117.0	303	14.80	1.02
3.470	20,356	11,330	203.7	592	22.76	1.99

Table III: % Total Solids Determination of Black Liquor

BEFORE DRYING

	Static Mixer			
	Initial		Final	
	1	2	1	2
Dish & liquor (g)	70.5068	76.4229	72.7774	71.6762
Dry Dish (g)	60.0881	69.2295	60.3637	58.4719
Liquor Wt. (g)	10.4187	7.1934	12.4137	13.2043

AFTER DRYING

Dish & liquor (g)	65.9324	73.1895	67.2516	65.8800
Dry Dish (g)	60.0881	69.2295	60.3637	58.471
Liquor Wt. (g)	5.8443	3.9600	6.8879	7.4081
% Total Solids	56.2	55.0	55.3	56.1

Table III: (Cont.) % Total Solids Determination of Black Liquor

BEFORE DRYING

<div align="center">Empty Pipe</div>

	Initial		Final	
	1	2	1	2
Dish & liquor (g)	44.5038	77.8038	73.0507	72.9300
Dry dish (g)	37.1556	62.1539	60.5246	59.6045
Liquor Wt. (g)	7.3482	15.6499	12.5261	13.3255

AFTER DRYING

	1	2	1	2
Dish & liquor (g)	41.2072	71.0469	67.5158	67.0338
Dry dish (g)	37.1556	62.1539	60.5246	59.6045
Liquor Wt. (g)	4.0516	8.8930	6.9912	7.4293
% Total Solids	55.2	56.7	55.8	55.7

Overall Average % Total Solids = 55.75%
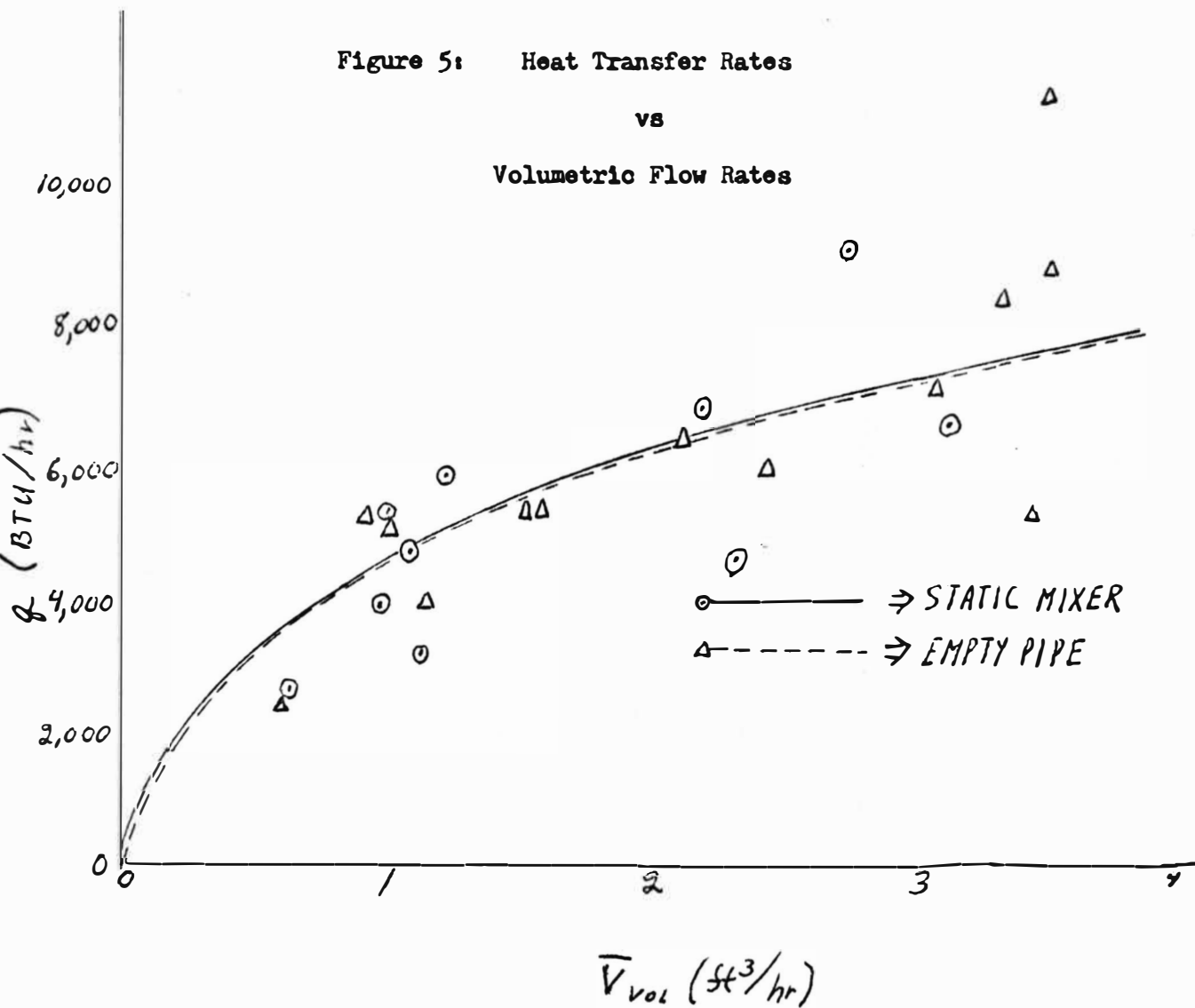
Figure 5: Heat Transfer Rates vs Volumetric Flow Rates
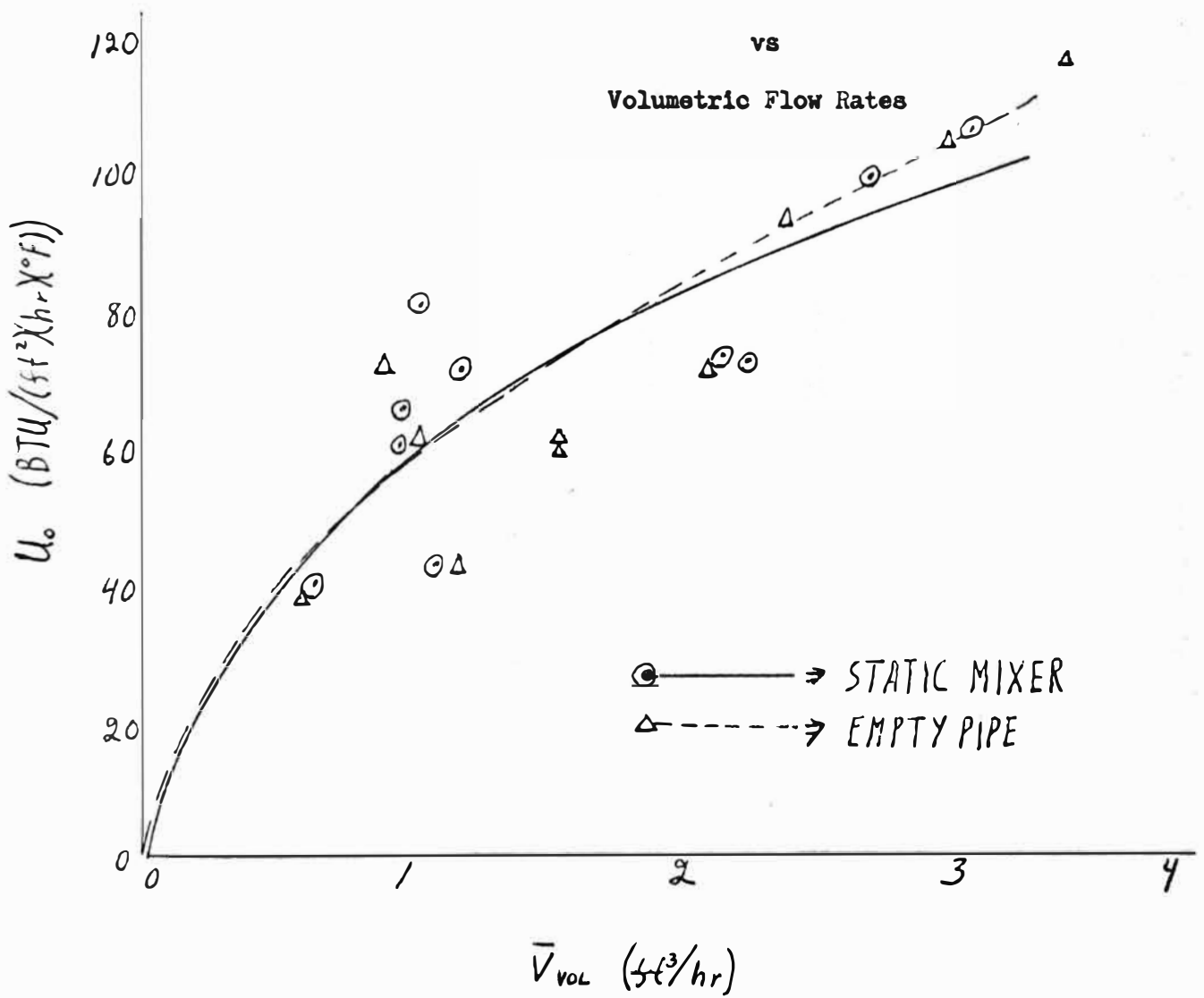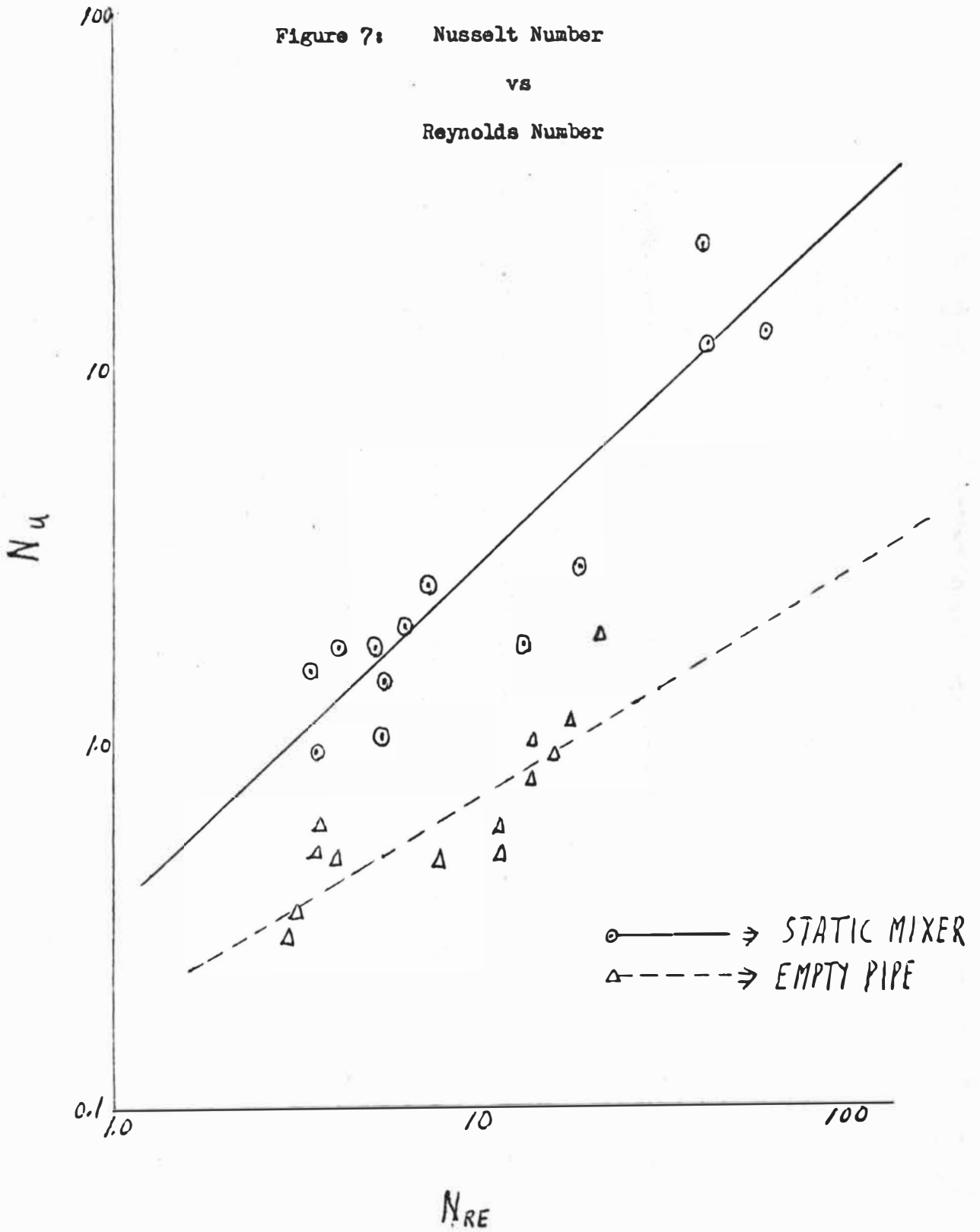
Figure 6: Overall Heat Transfer Coefficients

vs

Volumetric Flow Rates

Figure 7:   Nusselt Number
vs
Reynolds Number

while that of mild steel is 26 BTU/(ft)(hr)(^{O}F). This difference

in conductivities has a considerable effect on the heat transfer in

an operation, such as that used in this experiment, where flow rates

are very low. Any graphical enhancement developed by the Static

Mixer unit are offset by the increased transfer of heat in the empty

pipe due to the lower resistance of the metal.

Further evidence that the Static Mixer does enhance heat transfer

is illustrated in Figure 7 where the Nusselt number is plotted against

the Reynolds number. The Nusselt number is dependent on the inside

film coefficient and the thermal conductivity of the metal wall.

The enhancement of of the inside film coefficient using the Static

Mixer is evident. For example, at a Reynolds number of 5, the Nusselt

number using the Static Mixer is 1.15 while that using the empty

pipe is 0.46. At a Reynolds number of 20, the Nusselt number is 5.8

using the Staic Mixer while it is only 1.04 using the empty pipe.

As stated earlier, the overall heat transfer coefficient is highly

dependent on the inside film coefficient. It appears from these

results that the Static Mixer is reducing the the viscous film layer

which limits the transfer of heat.

Conclusions

The Static Mixer unit does decrease the resistance of the in-
side film layer a slight, but significant, amount. As seen in the
plot of Nusselt number versus Reynolds number, the enhancement in the
inside film coefficient is evident in the laminar areas of flow used.
If higher viscosities would have been present, a greater increase in
heat transfer caused by the Static Mixer, as compared to the empty
pipe, may have occured. Presently, when most initial and final evap-
orating systems are operated to get a total solids concentration of
50 to 60%, it does not appear that it would be economically feasable
to employ these units. However, as newer recovery operations demand
higher concentrations, I believe that the Static Mixer's application
in the evaporating stages will become highly feasable and necessary.
Conclusions presented here are limited to the laminar regions of flow.
Large scale evaporators, however, operate in turbulent regions.
Therefore, I recommend that further experimentation be carried out at

higher concentrations and flow rates to develop means by which

the Static Mixer unit can be economically used in the evaporation

process.

Literature Cited

1. Babcock&Wilcox, "STEAM/its generation and use" 38th ed., New York, Babcock & Wilcox Co., 1972, pp. 26-1, 26-6.

2. Gorman, P. A., "Six Major Problems", PULP & PAPER, Vol. 47, No. 6, June, 1973, pp. 50-51.

3. Lowe, K. E., "TAPPI environmental conference reveals slow technical progress", PULP & PAPER, Vol. 47, No. 8, July, 1973, p. 71.

4. Joint Textbook Committee of the Paper Industry, "THE PULPING OF WOOD" 2nd ed., McGraw-Hill, 1969, Vol. 1, pp. 508,509.

5. McCabe, W. L., and Smith, J. C., "Unit Operations of Chemical Engineering" 2nd ed., McGraw-Hill, 1967, p. 440.

6. Backteman, E. H., and Marr, R. Y., "The Art of Obtaining High Solids Black Liquor for Direct Firing", PULP & PAPER MAGAZINE of CANADA, Vol. 72, No. 12, December, 1971, pp. 79-84.

7. Pattison, D. A., "Motionless Inline Mixers Stir Up Broad Interest", CHEMICAL ENGINEERING, Vol. 76, No. 11, May 19, 1969, pp. 94-96.

8. KENICS CATALOG, KENICS Corp., Danvers, Mass.,(KTEK-I).

9. Chen, S. J., and MacDonald, A. R., "Motionless Mixers for Viscous Polymers", CHEMICAL ENGINEERING, Vol. 80, No. 7, March 19, 1973, pp. 105-110.

10. TAPPI, Vol. 36, No.6, June,1973, pp. 272,273.