MASS TRANSFER IN A PACKED BED REACTOR AT LOW REYNOLDS NUMBERS: THE HYDROGENATION OF ETHYLENE TO ETHANE ON NICKEL CYLINDERS

By

BERRY CRAIN, JR.

Bachelor of Science

Mississippi State University

Starkville, Mississippi

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Thesis Approved:

J. W. Fulton
Thesis Adviser

John B West

K C Chao

J. H. Boggs
Dean of the Graduate School

PREFACE

Data were taken on mass transfer in a packed, catalytic bed. The reaction studied was the hydrogenation of ethylene to ethane catalyzed by nickel on alumina cylinders. The results are presented in the form of j-factors for mass transfer correlated against the boundary layer Reynolds number.

I am especially grateful to Dr. James W. Fulton, my Research Adviser, for his interest and helpful advice. I am also grateful to Dr. Robert N. Maddox and Dr. John B. West for serving on my Research Advisory Committee and for their helpful suggestions. Dr. John H. Erbar, Dr. Kenneth J. Bell, and Professor Wayne C. Edmister gave graciously of their time during my graduate work. My research associate, John E. Klopp, has been of great assistance in this study.

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The unselfish sacrifices and unfailing interest of my wife, Diane, were invaluable to this study.

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CHAPTER I

INTRODUCTION

There is a great need for a dependable, straight-forward method for designing chemical reactors. Before any method can be perfected, the mass transfer aspects of a chemical reactor must be understood.

In this light, a study was made on mass transfer in a packed, catalytic bed. The reaction chosen was the hydrogenation of ethylene to ethane catalyzed by nickel on alumina cylinders. The packed bed reactor was operated in the laminar flow regime. There were several reasons for this selection. First of all, there is very little information in the literature on generalized mass transfer correlations for packed, catalytic bed reactors, especially for reactors operated in the laminar flow regime.

Secondly, there are several favorable characteristics of the hydrogenation of ethylene to ethane that make it an ideal reaction for this study:

1. the reaction proceeds without any side reactions;
2. the reaction takes place at reasonable temperatures and atmospheric pressure;
3. the reaction takes place only in the presence of a catalyst;
4. the reaction is practically irreversible;

5. the mechanism of the reaction is relatively simple and well understood.

The method currently used to describe mass transfer in packed, catalytic bed reactors is the correlation of j-factors for mass transfer against the Reynolds number. This correlation expresses mass transfer as a function of physical and transport properties of the reactants at the catalyst surface and in the bulk gas stream, the flow rate of the reactants, and the size and shape of the reactor and the catalyst particles.

The purpose of this study is to obtain a mass transfer correlation for a packed, catalytic bed reactor operating in the laminar flow regime.

CHAPTER II

LITERATURE SURVEY

Reaction Kinetics

There have been a number of studies on the reaction kinetics of the hydrogenation of ethylene to ethane on nickel catalysts. Crawford, Roberts, and Kemball (12), Laidler and Townshend (23), Jenkins and Rideal (19,20), Rideal and Taylor (33), and Beeck (3) have all made observations concerning the apparent reaction mechanism of the hydrogenation of ethylene to ethane on nickel films. However, since the author's study was conducted in the diffusion-controlled regime defined by Frank-Kamenetskii (13), no detailed inquiry into reaction rate-controlled kinetics need be made.

Pauls, Comings, and Smith (28) and Laidler and Townshend (23) made the important observation that the exposure of a nickel catalyst to either pure or excess ethylene affected the catalyst activity. In the author's study hydrogen was always introduced into the catalyst bed first and the hydrogen-to-ethylene ratio was never lower than four to one. Rideal and Taylor (33) noted that the exposure of an activated nickel catalyst to oxygen greatly inhibited the activity of the catalyst. In the present study oxygen was never allowed to contact the activated catalyst.

Mass Transfer

In catalyst beds made up of a porous catalyst, mass transfer processes occur in the pores inside of the catalyst pellets as well as in the stagnant gas film surrounding them. Thiele (40), Mingle and Smith (26), Schilson (37), Schilson and Amundson (38,39), Tinkler and Metzner (41), Weisz and Hicks (42), Wheeler (43), Aris (1), and Carberry (8) have all investigated transfer processes occurring inside porous catalysts. However, since Fulton (14) showed that, with a nickel on alumina catalyst in a system almost identical to the one used in the author's study, mass transfer processes occurring inside the catalyst were negligible in comparison to external surface mass transfer processes, no detailed discussion of internal mass transfer effects will be attempted. Fulton also showed that the use of bed diluent particles of a different size than the catalyst particles did not change the mass transfer processes.

Turning from effects occurring inside the catalyst particles to external surface effects, mass transfer through the stagnant gas film surrounding the catalyst particle becomes important. Theoretical approaches to the problem of stagnant gas film mass transfer have been offered by Carberry (7), Hoelscher (18), Rosner (34), Kusick and Happel (22), and Pfeffer and Happel (30). However, these approaches are difficult to apply and are not very useful in practice.

Perhaps the most useful approach to mass transfer in a packed, catalytic bed is the analogy of mass transfer to fluid

friction proposed by Chilton and Colburn (9). They defined a j-factor for mass transfer as follows:

$$j_D = (k_{Gi} p_f / G_M)(\mu/\rho \mathcal{D}_i)^{2/3}_{film} \qquad \text{(II-1)}$$

where:

j_D = mass transfer number; dimensionless

k_{Gi} = mass transfer coefficient; gm moles/cm^2-sec-atm

p_f = pressure factor, defined as the logarithmic mean value of the partial pressure over the boundary limits of the gas film; atm

G_M = superficial molal velocity of the fluid based on the total cross-sectional area of the bed; gm moles/cm^2-sec

μ = viscosity of the fluid; gm/cm-sec

ρ = density of the fluid; gm/cm^3

$\mathcal{D}_i$ = diffusion coefficient of component i; cm^2/sec.

Considerable mass transfer data have been correlated using the Chilton and Colburn j-factor. However, nearly all of these data were taken using non-reacting systems. Several of the correlations in which j_D was correlated with the Reynolds number are listed below:

$j_D = 16.8(N_{Re})^{-1.0}$	$N_{Re} < 40$		(16)
$j_D = 0.989(N_{Re})^{-0.41}$	$N_{Re} > 350$		(44)
$j_D = 1.82(N_{Re})^{-0.51}$	$45 < N_{Re} < 350$		
$j_D = 1.625(N_{Re})^{-0.507}$	$N_{Re} < 120$		(25)
$j_D = 0.687(N_{Re})^{-0.327}$	$N_{Re} > 120$		
$j_D = 0.18(N_{Re})^{-0.376}$	$1 < N_{Re} < 400$		(32)

$$j_D = 0.66(N_{Re})^{-0.46} \quad 0.17 < N_{Re} < 250 \qquad (2)$$

$$j_D = 0.606(N_{Re})^{-0.309} \quad 400 < N_{Re} < 10{,}000 \qquad (6)$$

(including axial mixing)

$$j_D = 0.506(N_{Re})^{-0.293} \quad 400 < N_{Re} < 10{,}000$$

(omitting axial mixing)

Mass transfer j-factors for non-reacting systems have also been correlated with modified Reynolds numbers, N_{Re}' and N_{Re}'', where:

$$N_{Re}' = N_{Re}/(1 - \epsilon) \qquad (II\text{-}2)$$

ϵ = void fraction of the packed bed

$$N_{Re}'' = S(N_{Re}')/6 \qquad (II\text{-}3)$$

S = shape factor

The correlations obtained are:

$$j_D = 0.84(N_{Re}'')^{-0.51} \quad 0.01 < N_{Re}'' < 50$$

$$j_D = 0.57(N_{Re}'')^{-0.41} \quad 50 < N_{Re}'' < 1000 \qquad (31)$$

$$j_D = (N_{Re}')^{-0.35} \quad 1 < N_{Re}' < 30 \qquad (10)$$

Satterfield and Resnick (35) correlated j_D with N_{Re} for a reacting system, the decomposition of hydrogen peroxide on metal spheres, obtaining the following correlation:

$$j_D = 0.724(N_{Re})^{-0.34} \quad 15 < N_{Re} < 161 \qquad (35)$$

By comparing these previous correlations, it is evident that there is considerable disagreement among them.

CHAPTER III

APPARATUS

The apparatus used in this study consisted of four basic units: feed system, reactor, temperature measuring system, and gas analysis system. A schematic diagram of the apparatus is presented in Figure 1 on page 8.

Feed System

The hydrogen and ethylene gases were fed from commercial cylinders using single-stage pressure regulators and pressure reducing needle valves.

The hydrogen was purified with a Deoxo catalytic purifier which reduced traces of oxygen to water. A heated Deoxo Model "C" catalytic purifier was used to remove oxygen and sulfur from the ethylene feed. After passing through the heated purifier, the ethylene passed through a copper coil to cool the gas to room temperature.

Both of the reactants then passed through one-eighth inch needle valves to further reduce the pressure and to provide fine control.

After the reactants passed through Drierite drying tubes to remove moisture, their volumetric flow rates were measured by capillary flowmeters. Triethylene glycol was chosen as the

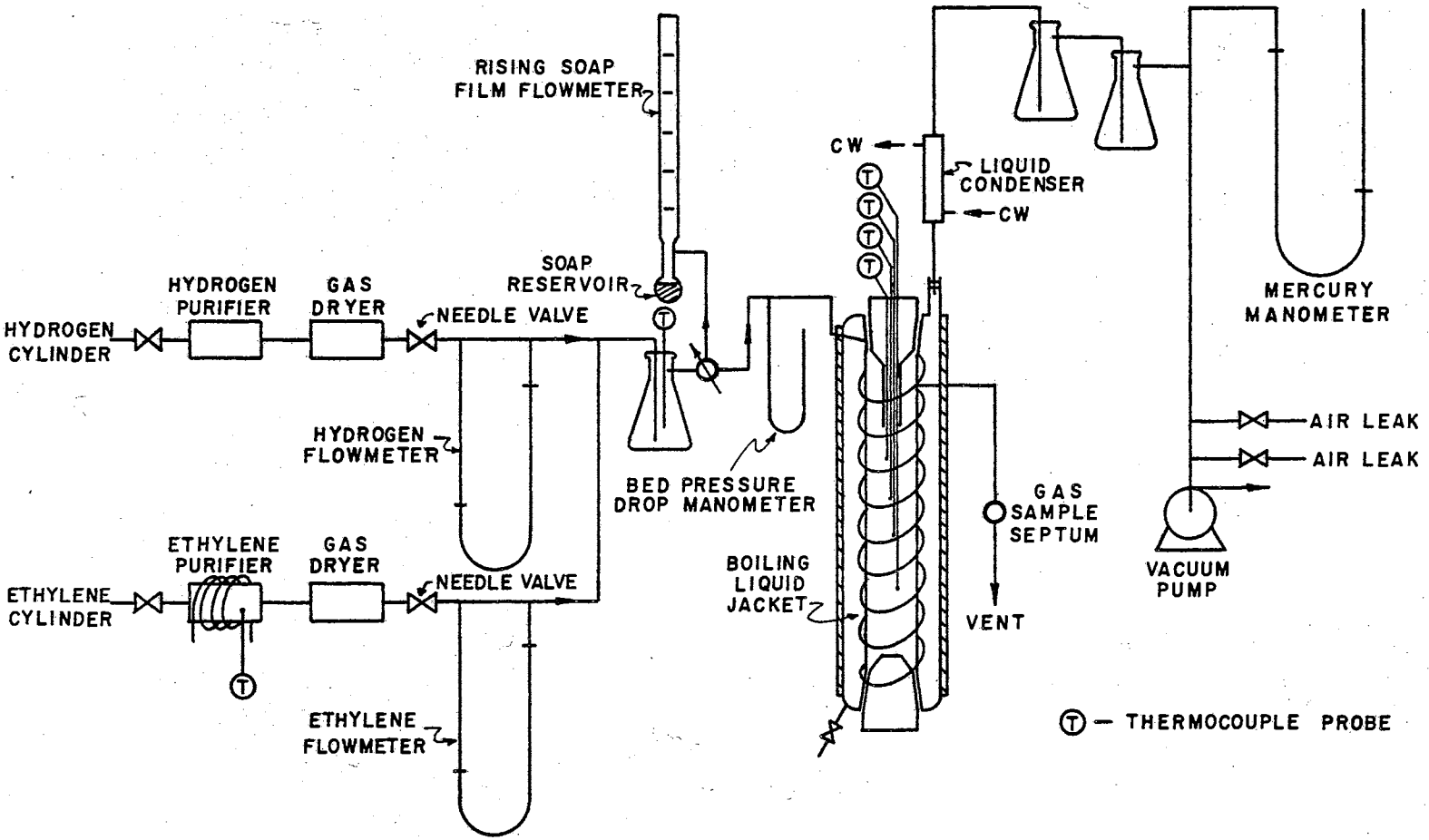

Figure 1. Schematic Diagram of Apparatus

manometric fluid because of its low vapor pressure. The flowmeters were calibrated against a rising soap-film flowmeter at the beginning and end of each run.

The reactants were thoroughly mixed in a 50-ml Erlenmeyer flask before entering the preheater.

Reactor

A photograph of the reactor is shown in Figure 2, page 10, and a detailed diagram of the reactor is shown in Figure 3, page 11. The reactant mixture passed through a preheater coil of 7-mm glass tubing which wrapped around the reaction tube and entered the chamber below the reaction tube. The reactants passed upwards through the reaction tube containing the catalyst bed and out the gas exit tube on the side of the reactor.

The preheater coil and reaction tube were surrounded by a boiling liquid which served the dual purpose of bringing the reactants to reaction temperature and maintaining a nearly constant bulk gas temperature in the reaction tube.

Heat was supplied to the boiling liquid by means of a coil of electrically heated resistance wire. Layers of asbestos tape provided both electrical insulation for the wire coil and heat insulation for the liquid jacket. The temperature of the boiling liquid jacket was controlled by regulating the vacuum on it using a vacuum pump and an air leak valve.

The top and bottom of the reaction tube were plugged with ground glass plugs. These plugs simplified packing and unpacking of the catalyst bed. A 14-mm glass tube built into the top plug

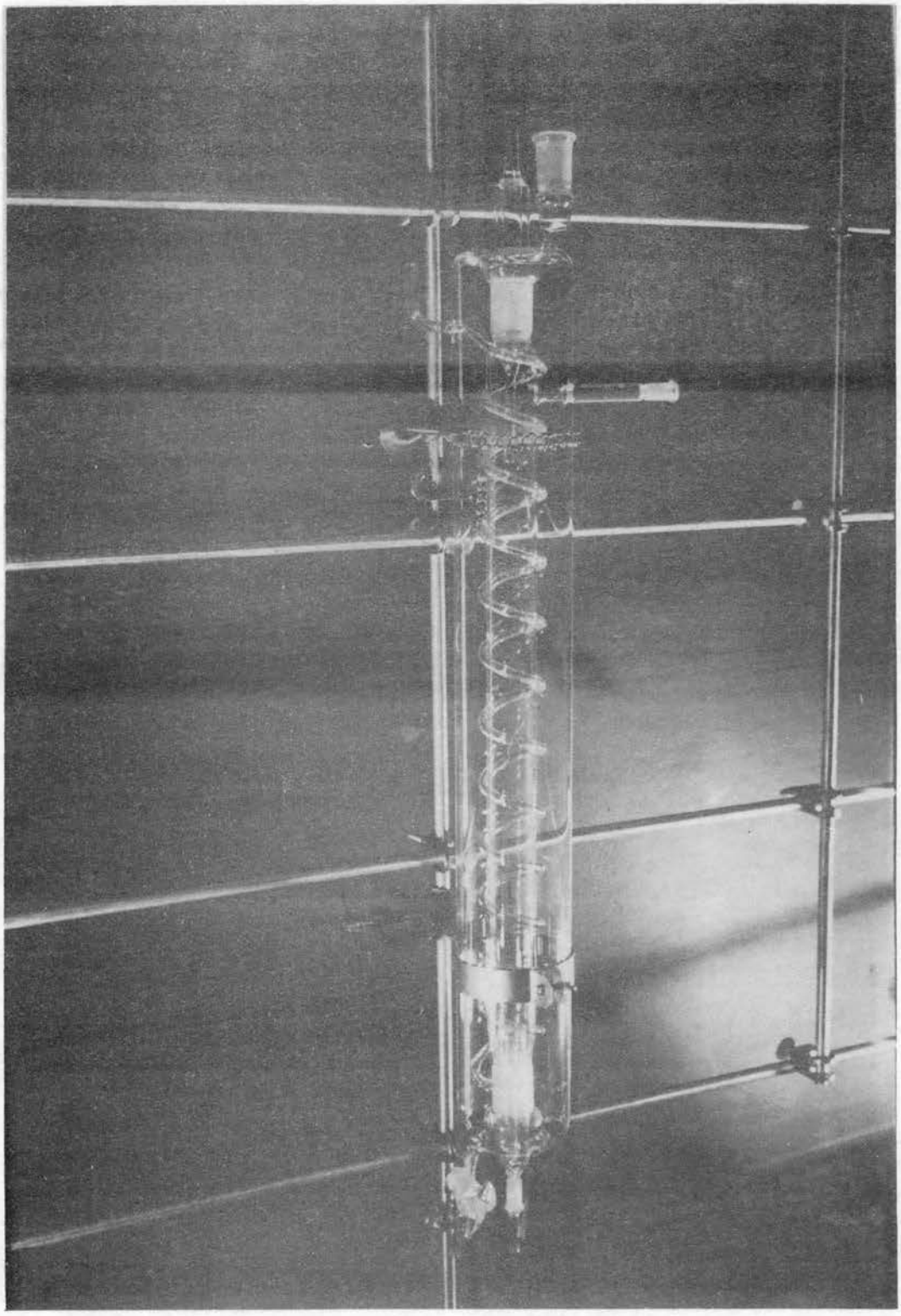

Figure 2. Photograph of Reactor

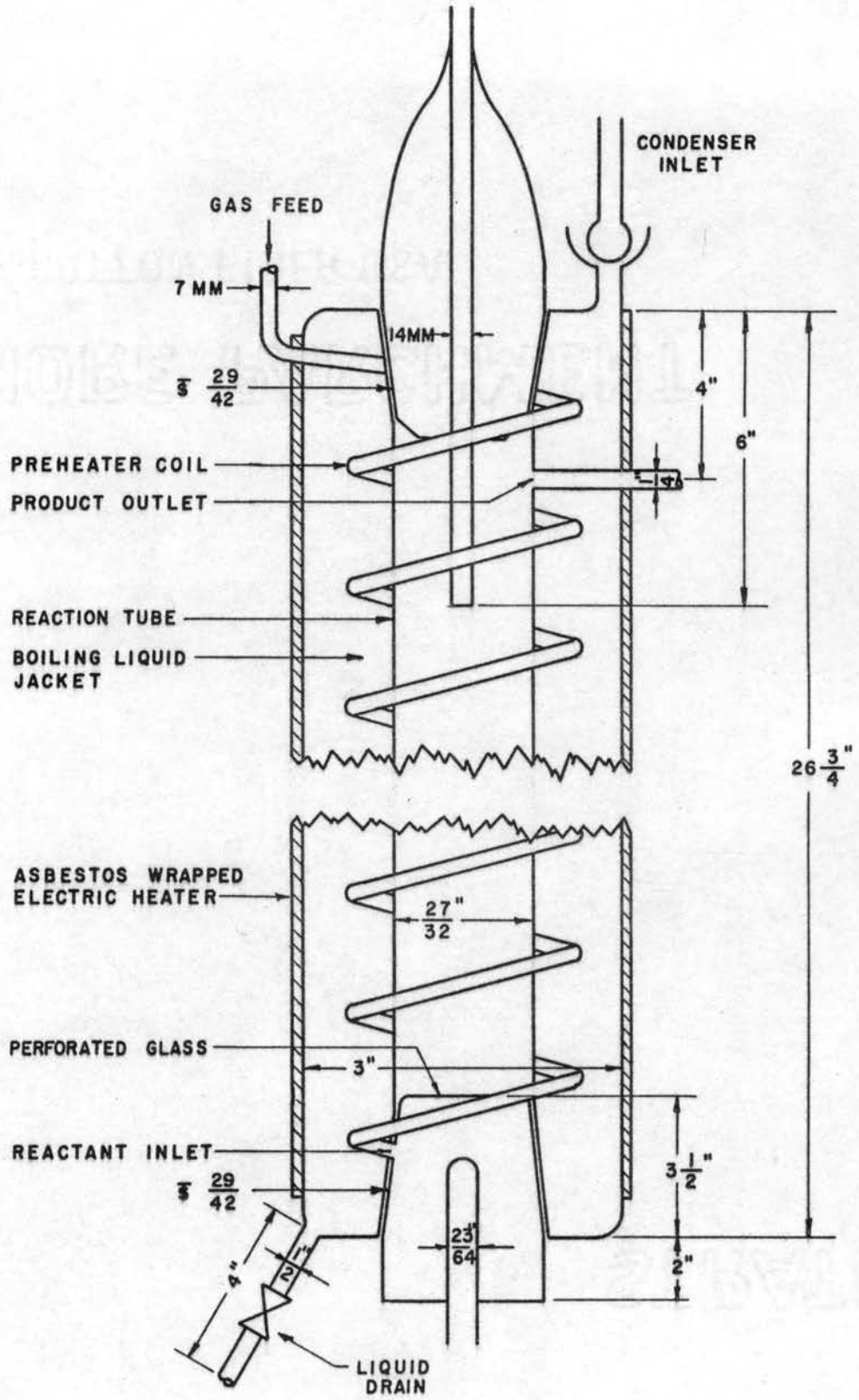

Figure 3. Detailed Diagram of Reactor

provided an exit tube for the thermocouple wires from the bed.

Temperature Measuring System

The entering and exit bulk-gas temperatures were measured by thermocouples inserted into 3-mm glass beads which were placed at the bottom and top of the catalyst bed. Catalyst surface temperatures were measured by thermocouples inserted into catalyst particles at the bottom and top of the bed. All of the thermocouples were iron-constantan. The potential of each thermocouple was measured with a Leeds and Northrup Model 8686 millivolt potentiometer.

Gas Analysis System

Gas analysis was performed on a thermal conductivity type gas chromatograph. The column used was a four-foot length of quarter-inch copper tubing, packed with 20-28 mesh silica gel. Helium was used as the carrier gas at a flow rate of 100-cc per minute. The column and thermal conductivity cell were maintained at a constant temperature of 56.5°C with a boiling acetone jacket.

CHAPTER IV

MATERIALS

Materials used for this study were the catalyst particles, the bed diluent, and the reactants hydrogen and ethylene.

Catalyst Particles

The catalyst particles were nickel on alumina in the form of cylinders averaging 3.08-mm in diameter and 3.55-mm in length. The catalyst, Girdler Catalyst No. T-310, sample No. 10-152, was supplied free of charge by Girdler Catalysts.

Bed Diluent

3-mm glass spheres were used as a bed diluent, being nearly the same size as the catalyst cylinders.

Reactants

The hydrogen, manufactured by the electrolytic process, was obtained from commercial sources. The hydrogen was about 99.9% pure, the impurities being primarily oxygen and water.

Ethylene was supplied free of charge by Phillips Petroleum Company. The mole percent purity by mass spectrometer was 99.3%, with trace impurities of acetylene, carbon monoxide, water, carbon dioxide, sulfur, and oxygen.

CHAPTER V

EXPERIMENTAL PROCEDURE

The description of the experimental procedure used in this study is presented in six sections: preparation of the temperature sensing system, method of packing the reactor, calibration of the flowmeters, reduction of the catalyst, reaction run, and analysis of the product gas stream.

Temperature Sensing System

In order to insert the thermocouples into the glass beads and catalyst particles, a small hole was abraded into each particle by means of a sand abrasive unit. This procedure formed holes which were of a slightly larger diameter than the thermocouple junction beads. Sauereisen ceramic adhesive cement was used to cement the thermocouple beads into the holes in the particles.

After allowing the cement to dry, the thermocouple lead wires were thoroughly cleaned with acetic acid, rinsed with distilled water, and dried. Three thin coats of Sauereisen were then applied to the wires, allowing the cement to dry after each application.

As soon as the bed was packed, the thermocouple lead wires were passed through the ground glass plug in the top of the reaction tube and soldered to a multi-point switch. The switch

was connected to the terminals of the potentiometer by means of two lead wires soldered to the common poles of the switch.

Packing the Reactor

The bottom ground glass plug was first inserted into the reactor and securely wired into place. A two-inch layer of glass wool was then placed at the bottom of the reaction tube to completely disperse the entering gas mixture. On top of this layer of glass wool was placed a glass bead containing a thermocouple. A three-inch layer of 3-mm glass beads was placed on top of this first glass bead. A catalyst particle containing a thermocouple was then placed on top of the glass beads, followed by another layer of glass beads. This same procedure was followed until the desired number of catalyst particles was in the bed. On top of the last layer of glass beads was placed a glass bead containing a thermocouple.

The number of catalyst particles in the bed varied from three to nine.

Calibration of Flowmeters

The flowmeters were calibrated before and after each run. The pressure drop across the capillary manometer type flowmeters was calibrated against the volumetric flow rate, which was measured by a rising soap-film flowmeter. The volumetric flow rate was obtained by dividing the volume of the flowmeter (100 cc) by the time required for the soap film to displace this volume.

A manometer was installed at a point in the line entering

the reactor to measure the pressure drop across the reactor.

Catalyst Reduction

Hydrogen was first fed into the reactor at the rate of one gram mole per hour to purge the catalyst bed. The hydrogen flow was maintained at this rate for one hour. Powdered Hitec heat transfer salt was then added to the reactor jacket and the heating coils were turned on. The temperature of the jacket was raised to around 150°C, the melting point of the Hitec. As the Hitec melted, more powdered salt was added to maintain the level in the jacket. About four hours were required to completely fill the jacket with molten salt.

At this point the current to the heating coils was increased and the temperature of the molten salt was slowly raised to 375°C. This temperature was maintained for ten hours and the hydrogen rate was continued at the rate of one gram mole per hour. The molten salt was then drained from the reactor, the heating coils were turned off, and the reactor was allowed to cool. The hydrogen flow was maintained during the cooling in order to keep the reduced catalyst bed free of oxygen.

Reaction Run

After the catalyst reduction operation, the liquid jacket was rinsed to remove any Hitec remaining and the jacket was filled to a point above the top of the catalyst bed with whatever liquid was required to control the temperature at the desired level. The reaction temperature was controlled by regulating

the boiling point of the liquid in the jacket by varying the vacuum above it. The degree of vacuum was controlled by an air leak in the line from the liquid jacket to the vacuum pump. The degree of vacuum was measured by a mercury manometer connected to the same line. The liquid jacket was operated at total reflux, the vapor being condensed by a water-cooled condenser and returned immediately to the jacket.

After the reactor had reached the desired temperature, the hydrogen flow rate was adjusted to 2.0 cc/sec and the ethylene flow was begun and adjusted to 0.5 cc/sec. The four-to-one molar ratio of hydrogen to ethylene was held constant during all the reaction runs. A greater concentration of ethylene has been shown to contaminate the catalyst surface with acetylenic-type compounds (5).

After a twenty minute delay to permit the reactor to reach steady state, a sample of the reactant gas mixture was taken to ensure that only ethylene and hydrogen were present in the reactant gas mixture before it entered the reactor. Four product gas samples were then taken with an interval of eight minutes between each sample. The thermocouple readings were noted and recorded while each gas sample was passing through the chromatograph column.

The flow rates of hydrogen and then ethylene were increased to the next desired value and the procedure was repeated. The reaction run was continued in this manner until the desired range of flow rates had been spanned. The ethylene and hydrogen flow rates were then returned to their original values, 2.0 cc/sec of

hydrogen and 0.5 cc/sec of ethylene, and samples were taken under these conditions to detect any change in catalyst activity. At the end of the run, the ethylene flow was stopped, the heating coils were turned off, and the reactor was allowed to cool with hydrogen flowing through the bed.

Product Stream Analysis

Samples were taken from the reactant gas stream and the product gas stream through rubber septums with a 5-cc gas syringe. The samples were injected immediately into the chromatograph injection port.

The resulting chromatograph curves were analyzed by the curve area-weight fraction method applicable to short-chained alkenes and alkanes (24,29) in which the ratio of the area under the ethane curve to the area under the ethylene curve, corrected for attenuation, is equal to the ratio of the weight fractions of the two components.

CHAPTER VI

EXPERIMENTAL RESULTS

Experimental Data

The experimental data in this study were taken in the laminar flow regime, the Reynolds number varying from approximately 0.2 to 3.0. This limited range of operation was necessary in order to keep the pressure drop across the catalyst bed at a minimum. The maximum pressure drop encountered was 0.8 in. triethylene glycol.

Experimental runs were made at bulk gas temperatures of 97°C and 68°C using nine catalyst particles in the bed. With a catalyst bed containing three catalyst particles, runs were made at bulk temperatures of 95°C, 64°C, and 30°C. An experimental run entailed varying the flow rate while holding the bed packing and bulk temperature constant. Duplicate runs were made to check for reproducibility.

The percent conversion and catalyst surface temperature varied with flow rate, the percent conversion decreasing with an increase in flow rate and the catalyst surface temperature increasing with an increase in flow rate. The dependence of the conversion on the Reynolds number is shown in Figure 4 on page 20. The dependence of the catalyst surface temperature on the Reynolds number is shown in Figure 5 on page 21.

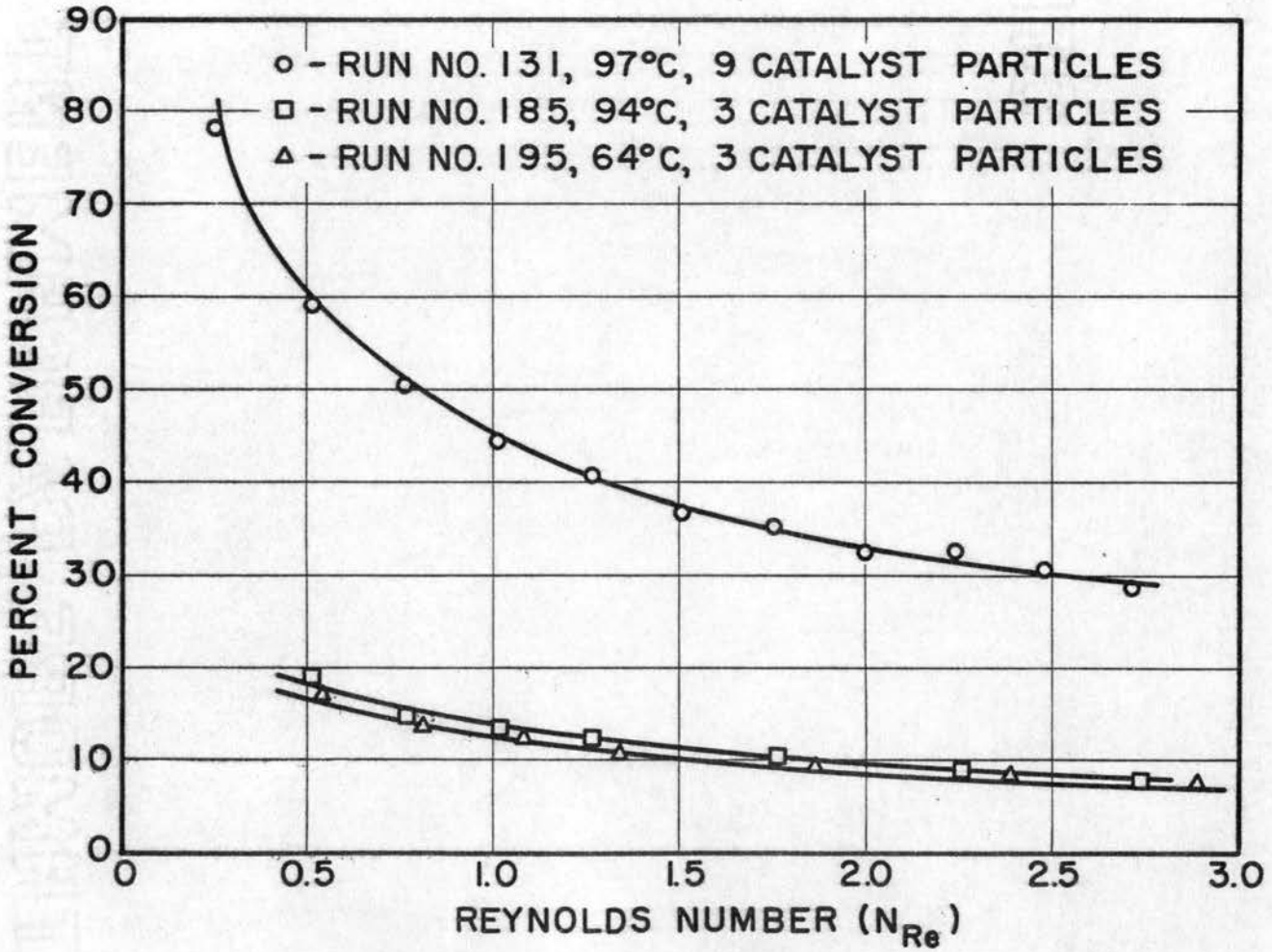

Figure 4. Dependence of Conversion upon Reynolds Numbers

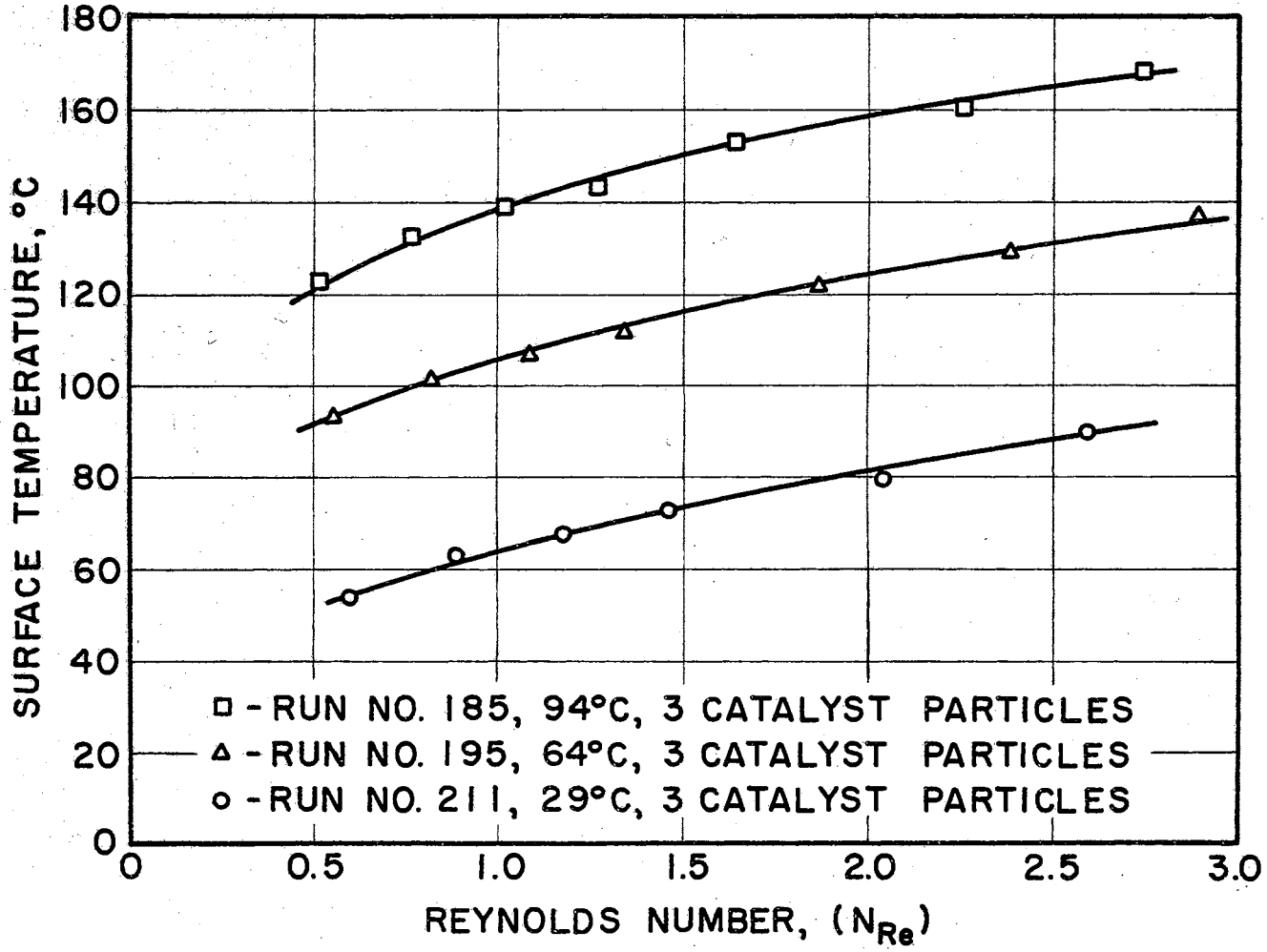

Figure 5. Dependence of Surface Temperature upon Reynolds Number

Calculations

The mass transfer coefficient was calculated by the following equation (36):

$$k_{G_e} = \frac{N_e}{(P_{b_e} - P_{s_e})} \qquad \text{(VI-1)}$$

where:

N_e = ethylene flux, gm. moles ethylene per sec. per square cm. of external catalyst surface area

$(P_{b_e} - P_{s_e})$ = difference in partial pressure of ethylene across the stagnant gas film, atm.

The j-factor for mass transfer was calculated by the following equation (9):

$$j_D = (k_{G_e} p_f / G_{M_e})(N_{Sc})^{2/3} \qquad \text{(II-1)}$$

where:

p_f = pressure factor for diffusion through a stagnant gas film, atm.

G_{M_e} = molar flow rate of ethylene based on the reactor cross-section, gm. moles ethylene per sec. per square cm. of reactor cross-sectional area

N_{Sc} = Schmidt number at average film conditions

A sample calculation of the j-factor and the Reynolds number is made in Appendix A. Assumptions necessary in making the calculations are also found there. The particulars of the computer program used to calculate the j-factors and Reynolds numbers are presented in Appendix B, and the computer program

used to curve fit the data is described in Appendix C. Experimental data and calculated results are shown in Appendix D.

CHAPTER VII

DISCUSSION OF RESULTS

Interpretation of Data

It can be seen from Figure 4 that the percent conversion decreases as the flow rate increases. It can also be seen that the percent conversion was directly proportional to the amount of catalyst in the bed and relatively independent of the bulk gas temperature. For example, Run No. 131 had nine catalyst particles in the bed and Run No. 185 had three catalyst particles in the bed. Both of these runs were made at practically the same bulk gas temperature. As seen in Figure 4, the percent conversion for Run No. 131 was approximately three times the percent conversion for Run No. 185 at a given flow rate. In regard to the independence of the conversion with respect to the bulk gas temperature, Figure 4 shows that Run No. 185 and Run No. 195, which were both made with three particles in the bed, yield approximately the same conversion curves even though they were made at markedly different bulk gas temperatures.

From Figure 5 it can be seen that the catalyst surface temperature increased with increasing flow rate. However, the temperature drop between the catalyst surface and the bulk gas stream is practically the same for all three runs at a given flow rate.

Correlation of Data

There is some question as to whether the calculated results of the runs using nine catalyst particles in the bed are sufficiently accurate. This question arises from the fact that the calculation of the mass transfer coefficient involves the use of the mean partial pressure of ethylene in the bulk gas stream. In the runs using nine catalyst particles in the bed, the conversion was sometimes as high as 78% and the ethylene partial pressure varied from 0.2 atm. at the bottom of the bed to 0.052 atm. at the top of the bed. It is believed that this large variation caused slightly erroneous calculated results and therefore no attempt was made to correlate the nine catalyst particle runs and the three catalyst particle runs together. Instead, the correlations were performed separately and the proposed j-factor correlation is based solely on the runs made with three catalyst particles in the bed. Figure 6 on page 26 shows the results of the correlations using all of the data points and the solid line represents the correlation of the three particle runs after data points with a percent deviation of more than three times the average percent deviation were removed. A least squares regression for 331 data points of the three particle runs gave: $j_D = 2.82(N_{Re})^{-0.541}$. The removal of 21 of the three particle data points caused the standard estimate of error to change from 0.261 to 0.160 and the average percent deviation to change from 6.47% to 4.76%.

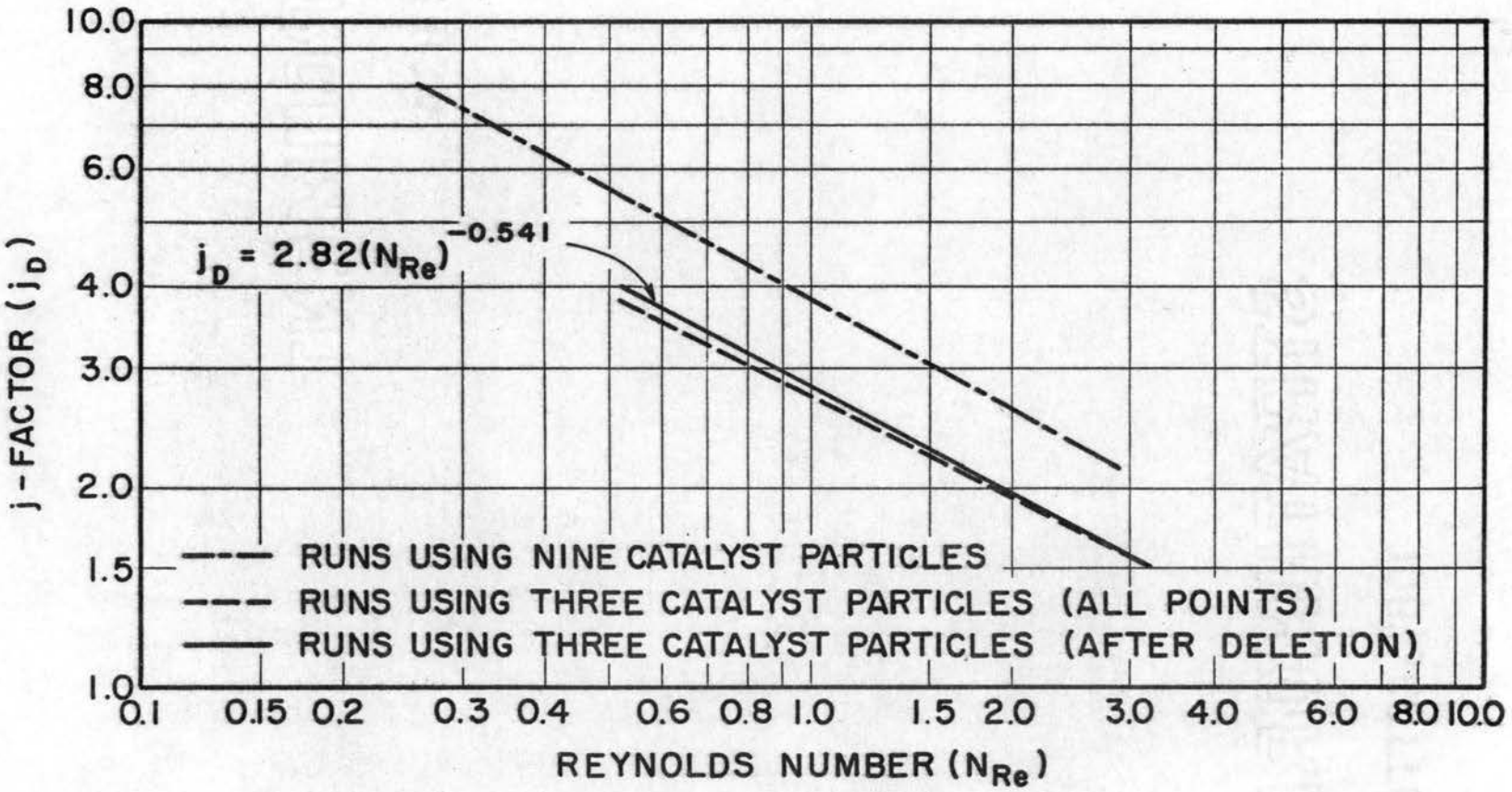

Figure 6. Dependence of j-factor for Mass Transfer upon Reynolds Number; Results of Curve Fit

Comparison with Previous Correlations

The correlation obtained is not in close agreement with correlations proposed in previous investigations. This may be explained by the fact that most previous mass transfer correlations were based on non-reacting systems. The correlation offered by Satterfield and Resnick (35) is based on a reacting system, but their study was carried out completely in the turbulent flow regime, whereas flow in the author's study was in the laminar regime. The author's correlation agrees best with the one proposed by McCune and Wilhelm, as can be seen in Figure 7 on page 28, in which several of the literature correlations are presented along with the author's.

The correlation obtained also does not agree with the heat transfer correlation proposed by Klopp (21) using the same data.

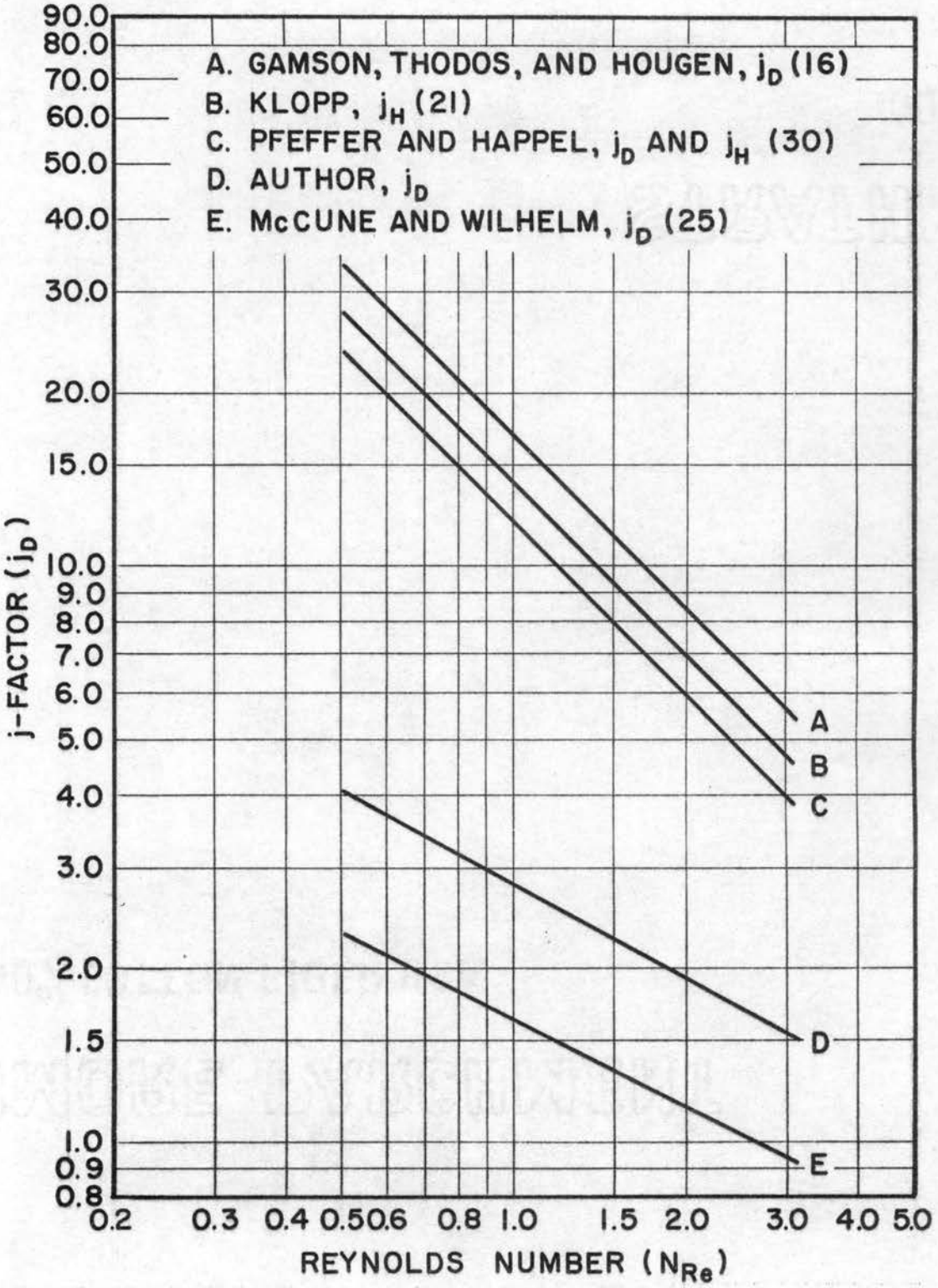

Figure 7. Presentation of Selected Literature Correlations

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

Mass transfer in a packed, catalytic bed may be described by the correlation of j-factors for mass transfer with the Reynolds number for flow through a packed bed. The correlation obtained from this study of the hydrogenation of ethylene to ethane catalyzed by nickel on alumina cylinders gives the relationship:

$$j_D = 2.82\ (N_{Re})^{-0.541}$$

This correlation was obtained from data taken on a packed bed containing three catalyst particles. Data taken on a bed containing nine catalyst particles was not used in the correlation due to the high degree of conversion obtained from this packing.

In order to substantiate or disprove results obtained in this study, the following recommendations for future work may be made:

1. Collect and correlate data for several different sets of reactants.
2. Collect and correlate data for several different sizes, shapes, and varieties of catalyst particles.
3. Collect and correlate data for several different sizes of reaction tubes.

NOMENCLATURE

D_p = Particle diameter; cm.

$\mathcal{D}_i$ = Diffusion coefficient; cm^2/sec.

F = Molar flow rate; gm moles/sec.

G_M = Superficial molar flow rate; gm moles/cm^2-sec.

G_m = Superficial mass flow rate; gm/cm^2-sec.

j_D = j-factor for mass transfer; dimensionless.

k_{Gi} = Mass transfer coefficient; gm moles/cm^2-sec-atm.

M_i = Molecular weight; gm/gm mole.

n = Number of gm moles; gm moles.

N = Number of catalyst particles in bed.

N_i = Molar flux; gm moles/cm^2-sec.

N_{Re} = Reynolds number ($D_p G_m/\mu$); dimensionless.

N_{Re}' = Modified Reynolds number, $N_{Re}/(1 - \epsilon)$; dimensionless.

N_{Re}'' = Modified Reynolds number, $SN_{Re}'/6$; dimensionless.

N_{Sc} = Schmidt number, ($\mu/\rho\mathcal{D}_i$); dimensionless.

p = Pressure; atm.

R = Gas constant; atm-cm^3/gm mole-°K.

S = Shape factor; dimensionless.

T = Temperature; °C.

V = Volume; cm^3.

W = Weight of catalyst; gm.

ϵ = Void fraction of bed; dimensionless.

μ = Viscosity; gm/cm-sec.

ρ = Density; gm/cm^3.

ϕ = Shape factor; dimensionless.

Subscripts

av = Arithmetic average quantity.

b = Bulk gas phase.

c = Critical condition.

e = Ethylene.

i = Component i.

s = Catalyst surface.

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APPENDIX A

SAMPLE CALCULATIONS

The j-factor for mass transfer and the Reynolds number are calculated for the first sample in run number 216. The ethylene flow rate was 1.0 cc/sec, the hydrogen flow rate was 4.0 cc/sec, and there were three catalyst particles in the bed. The surface temperature of the catalyst particle at the top of the bed was 54.6°C and the surface temperature of the catalyst particle at the bottom of the bed was 53.4°C. The average bulk temperature was 29.8°C and the room temperature was 33.2°C. The ratio of the ethane peak area to the ethylene peak area (from the chromatograph chart), corrected for attenuation, was 0.154. The surface area of the catalyst particles was 1.43 cm^2.

1. Molar flow rates:

Hydrogen rate = (4.0 cc/sec)(1 gm mole/22,410 cc)(273°K/306.2°K)

= 1.59×10^{-4} gm mole/sec

Ethylene rate = 3.98×10^{-5} gm mole/sec

2. Mole percent conversion (24,29):

Peak area ratio = Mass ratio = 0.154 gm ethane/gm ethylene

Mole ratio = (0.154 gm ethane/gm ethylene)(28.05 gm ethylene/gm mole ethylene)(1/30.07 gm mole ethane/gm ethane)

= 0.144 gm mole ethane/gm mole ethylene

Basis: 1 gm mole ethylene

0.144 gm mole ethane

Original gm mole ethylene = 1.0 + 0.144 = 1.144 gm mole ethylene

Fraction conversion = 0.144/1.144 = 0.126

Percent conversion = (0.126)(100) = 12.6%

3. Mole fractions in exit gas stream:

Basis: 100 gm moles of entering mixture

80 gm moles hydrogen

20 gm moles ethylene

100 gm moles mixture

Ethane formed = (0.126)(20) = 2.52 gm moles ethane

Ethylene remaining = 20 - 2.52 = 17.48 gm moles ethylene

Hydrogen remaining = 80 - 2.52 = 77.48 gm moles hydrogen

Total gm moles remaining = 2.52 + 17.48 + 77.48 = 97.48 gm moles

Mole fraction hydrogen = 77.48/97.48 = 0.795

Mole fraction ethylene = 17.48/97.48 = 0.179

Mole fraction ethane = 2.52/97.48 = 0.0258

4. Average film temperature:

Average surface temperature = (54.6 + 53.4)/2 = 54.0°C

Average bulk temperature = 29.8°C

Average film temperature = (54.0 + 29.8)/2 = 41.9°C

5. Viscosities (17):

Viscosities in bulk gas at bottom of bed:

μ(hydrogen) = 0.901 x 10^{-4} gm/cm-sec

μ(ethylene) = 1.04 x 10^{-4} gm/cm-sec

Viscosities in surface gas at bottom of bed (assume all hydrogen):

μ(hydrogen) = 0.945 x 10^{-4} gm/cm-sec

Viscosities in bulk gas at top of bed:

μ(hydrogen) = 0.901 x 10^{-4} gm/cm-sec

μ(ethylene) = 1.04 x 10^{-4} gm/cm-sec

μ(ethane) = 0.94 x 10^{-4} gm/cm-sec

Viscosities in surface gas at top of bed (assume all hydrogen):

μ(hydrogen) = 0.950 x 10^{-4} gm/cm-sec

Viscosity of bulk gas at bottom of bed:

μ(bulk) = (0.8)(0.901 x 10^{-4}) + (0.2)(1.04 x 10^{-4})

= 0.929 x 10^{-4} gm/cm-sec

Viscosity of bulk gas at top of bed:

μ(bulk) = (0.795)(0.901 x 10^{-4}) + (0.179)(1.04 x 10^{-4})

+ (0.0258)(0.94 x 10^{-4}) = 0.927 x 10^{-4} gm/cm-sec

Viscosity of surface gas at bottom of bed:

μ(surface) = 0.945 x 10^{-4} gm/cm-sec

Viscosity of surface gas at top of bed:

μ(surface) = 0.950 x 10^{-4} gm/cm-sec

μ_{AV}(bulk) = (0.929 x 10^{-4} + 0.927 x 10^{-4})/2

= 0.928 x 10^{-4} gm/cm-sec

μ_{AV}(surface) = (0.945 x 10^{-4} + 0.950 x 10^{-4})/2

= 0.948 x 10^{-4} gm/cm-sec

μ_{AV}(film) = (0.928 x 10^{-4} + 0.948 x 10^{-4})/2

= 0.938 x 10^{-4} gm/cm-sec

6. Diffusion coefficient (4):

Assume diffusion of ethylene in hydrogen is controlling.

$$p\mathcal{D}_{AB}\,(p_{c_A}p_{c_B})^{1/3}(T_{c_A}T_{c_B})^{5/12}(1/M_A + 1/M_B)^{1/2} = 2.745 \times 10^{-4}\,(T/\sqrt{T_{c_A}T_{c_B}})^{1.823} \qquad \text{(A-1)}$$

A = ethylene

B = hydrogen

where:

p = pressure; atm = 1 atm (assumed)

p_c = critical pressure; atm

T_c = critical temperature; °K

M = molecular weight

$$(p_{c_A}p_{c_B})^{1/3} = (50.0 \times 12.8)^{1/3} = 8.61$$

$$(T_{c_A}T_{c_B})^{5/12} = (282.4 \times 33.3)^{5/12} = 45.0$$

$$(1/M_A + 1/M_B)^{1/2} = (1/28.05 + 1/2.016)^{1/2} = 0.726$$

$$(T_{c_A}T_{c_B})^{1/2} = (282.4 \times 33.3)^{1/2} = 97.0$$

Average film temperature = 41.9°C = 314.9°K

$$\mathcal{D}_{AB} = (2.745 \times 10^{-4})(314.9/97.0)^{1.823}(8.61)(45.0)(0.726)$$

$$= 0.664\ cm^2/sec$$

7. Densities:

$$n/V = p/RT \qquad \text{(A-2)}$$

p = 1 atm (assumed)

R = 82.06 atm-cm^3/gm mole-°K

Bulk molar densities:

$$(n/V)_{bottom} = 1/(82.06)(302.8) = 4.02 \times 10^{-5}\ gm\ mole/cm^3$$

$$(n/V)_{top} = 1/(82.06)(302.8) = 4.02 \times 10^{-5}\ gm\ mole/cm^3$$

Surface molar densities:

$(n/V)_{bottom} = 1/82.06)(326.4) = 3.73 \times 10^{-5}$ gm mole/cm^3

$(n/V)_{top} = 1/(82.06)(327.6) = 3.72 \times 10^{-5}$ gm mole/cm^3

Bulk mass densities:

ρ(bottom) = $(4.02 \times 10^{-5}$ gm mole/cm$^3)(0.8 \times 2.016$

$+ 0.2 \times 28.05$ gm/gm mole)

$= 2.90 \times 10^{-4}$ gm/cm^3

ρ(top) = $(4.02 \times 10^{-5}$ gm mole/cm$^3)(0.795 \times 2.016$

$+ 0.179 \times 28.05 + 0.0258 \times 30.07$ gm/gm mole)

$= 2.98 \times 10^{-4}$ gm/cm^3

Surface mass densities (assume all hydrogen):

ρ(bottom) = $(3.73 \times 10^{-5}$ gm mole/cm$^3)(2.016$ gm/gm mole)

$= 7.50 \times 10^{-5}$ gm/cm^3

ρ(top) = $(3.72 \times 10^{-5}$ gm mole/cm$^3)(2.016$ gm/gm mole)

$= 7.50 \times 10^{-5}$ gm/cm^3

ρ_{AV}(bulk) = $(2.90 \times 10^{-4} + 2.98 \times 10^{-4})/2$

$= 2.94 \times 10^{-4}$ gm/cm^3

ρ_{AV}(surface) = $(7.50 \times 10^{-5} + 7.50 \times 10^{-5})/2$

$= 7.50 \times 10^{-5}$ gm/cm^3

ρ_{AV}(film) = $(2.94 \times 10^{-4} + 7.50 \times 10^{-5})/2$

$= 1.84 \times 10^{-4}$ gm/cm^3

8. Schmidt number:

$N_{SC} = (\mu/\rho\mathcal{D}_{AB})_{film} = (0.938 \times 10^{-4}$ gm/cm-sec$)/(1.84 \times 10^{-4}$ gm/cm$^3)(0.664$ cm^2/sec$) = 0.767$

9. Molar flow rate of ethylene based on reactor cross-section:

Ethylene flow rate = 3.98×10^{-5} gm mole/sec

Reactor cross-section = $\pi D^2/4 = \pi(3.4 \text{ cm})^2/4$

$= 9.10 \text{ cm}^2$

$G_{M_e} = (3.98 \times 10^{-5} \text{ gm mole/sec})/9.10 \text{ cm}^2$

$= 4.36 \times 10^{-6} \text{ gm mole/cm}^2\text{-sec}$

10. Total mass flow rate:

Hydrogen mass flow rate = $(1.59 \times 10^{-4} \text{ gm mole/sec})(2.016$ gm/gm mole)

$= 3.20 \times 10^{-4} \text{ gm/sec}$

Ethylene mass flow rate = $(3.98 \times 10^{-5} \text{ gm mole/sec})(28.05$ gm/gm mole)

$= 11.19 \times 10^{-4} \text{ gm/sec}$

Total mass flow rate = $3.20 \times 10^{-4} + 11.19 \times 10^{-4}$

$= 14.39 \times 10^{-4} \text{ gm/sec}$

11. Mass flow rate based on reactor cross-section:

$G_m = (14.39 \times 10^{-4} \text{ gm/sec})/9.10 \text{ cm}^2$

$= 1.58 \times 10^{-4} \text{ gm/cm}^2\text{-sec}$

12. Average mole fraction of ethylene:

Average mole fraction = $(0.2 + 0.179)/2$

$= 0.1895$

13. Mass Transfer coefficient (based on transfer of ethylene) (36):

Ethylene transferred = fraction conversion x ethylene flow rate

$= (0.126)(3.98 \times 10^{-5} \text{ gm mole/sec})$

$= 5.01 \times 10^{-6} \text{ gm mole/sec}$

Surface area of catalyst = 1.43 cm^2

Ethylene flux = $(5.01 \times 10^{-6} \text{ gm mole/sec})/1.43 \text{ cm}^2$

$$= 3.5 \times 10^{-6} \text{ gm mole/cm}^2\text{-sec}$$

$$k_{G_e} = \text{ethylene flux}/(p_{b_e} - p_{s_e}) \qquad \text{(A-3)}$$

where:

p_{b_e} = partial pressure of ethylene in the bulk gas stream

p_{s_e} = partial pressure of ethylene at the catalyst surface

Assume $p_{s_e} = 0$ for a diffusion-controlled reaction.

p_{b_e} = total pressure x average mole fraction = (1 atm)(0.1895)

= 0.1895 atm

k_{G_e} = $(3.5 \times 10^{-6}$ gm mole/cm^2-sec)/0.1895 atm

= 1.845×10^{-5} gm mole/cm^2-sec-atm

14. Pressure factor - p_f:

The pressure factor for diffusion through a stagnant gas film in binary gas mixtures is defined as the log-mean value of the partial pressure of the non-diffusing gas at the surface and in the bulk gas stream. It was shown by Fulton (14) that, for conditions identical to the ones in this study, the pressure factor is relatively constant and can be assumed to be 0.8 atm.

15. j-factor for mass transfer (9):

$$j_D = (k_{G_e} p_f / G_{M_e})(Sc)^{2/3} \qquad \text{(II-1)}$$

= $(1.845 \times 10^{-5}$ gm mole/cm^2-sec-atm)(0.8 atm)$(0.767)^{2/3}$/

$(4.36 \times 10^{-6}$ gm mole/cm^2-sec)

= 2.83

16. Reynolds number:

$$N_{Re} = (D_p G_m / \emptyset \mu) \qquad \text{(A-4)}$$

where:

$\emptyset$ = shape factor = 0.91 for cylinders (15)

D_p = particle diameter = 0.319 cm.

N_{Re} = (0.319 cm)(1.58 x 10^{-4} gm/cm^2-sec)/(0.91)(0.938 x 10^{-4} gm/cm-sec)

= 0.590

APPENDIX B

COMPUTER j-FACTOR CALCULATION PROGRAM

In order to facilitate calculation of the j-factors for mass transfer and the Reynolds numbers, a FORTRAN program was written for the IBM 1620 Digital Computer which read the raw laboratory data and calculated the desired results. This program could easily be changed to FORTRAN IV for the IBM 1410 Digital Computer by modification of the input, output, and format statements. A block diagram of the 1620 program appears on pages 47-49 followed by a list and explanation of the nomenclature used and a listing of the program.

Below is a description of the format necessary for the input data to this program.

Card No.	Columns	Format	Description	Units
1	1-5	I5	Run Number	
	6-10	I5	Number of catalyst particles without thermocouples	
	11-15	I5	Number of catalyst particles without thermocouples	
	16-20	I5	Number of data points in run	
2	1-10	F10.1	Total surface area of catalyst particles	cm^2
	11-20	F10.1	Diameter of catalyst particles	cm

Card No.	Columns	Format	Description	Units
2	21-30	F10.1	Diameter of reaction tube	cm
	31-40	F10.1	Shape factor	
Two cards for each data pt.				
(1)	1-10	F10.1	Potential of thermocouple measuring room temperature	millivolts
	11-20	F10.1	Potential of thermocouple measuring bottom bulk temp.	"
	21-30	F10.1	Potential of thermocouple measuring top bulk temp.	"
	31-40	F10.1	Potential of thermocouple measuring bottom surface temperature	"
	41-50	F10.1	Potential of thermocouple measuring top surface temp.	"
(2)	1.10	F10.1	Hydrogen flow rate	cm^3/sec
	11-20	F10.1	Ethylene flow rate	"
	21-30	F10.1	Ratio of ethane peak area to ethylene peak area, corrected for attenuation	

The results are punched out on cards, one card for each data point. Below is a description of the numbers punched out on each card in the order in which they are punched:

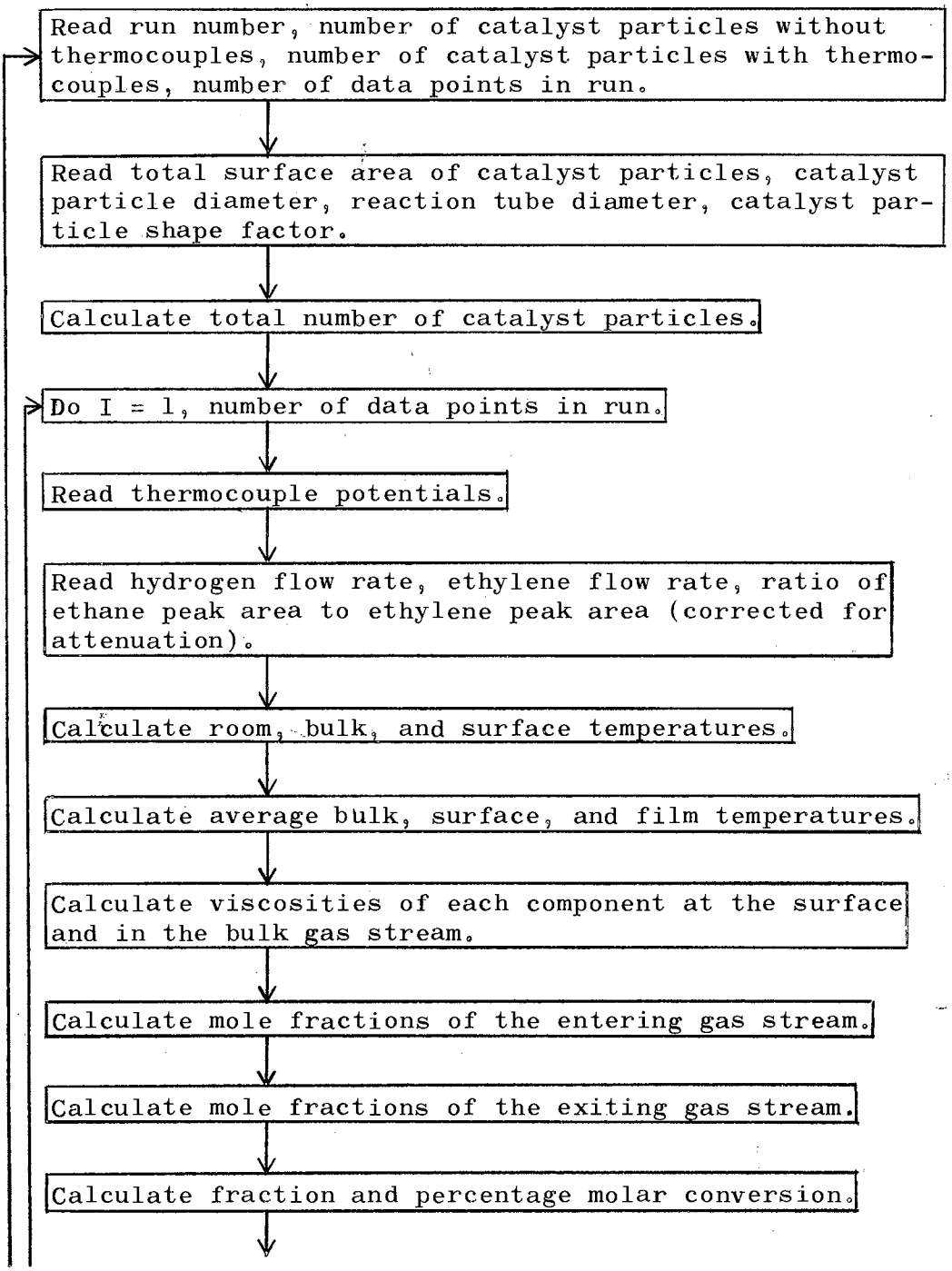
1. Run number
2. Total number of catalyst particles
3. Ethylene flow rate; cm^3/sec
4. Hydrogen flow rate; cm^3/sec
5. Percent molar conversion
6. Average catalyst surface temperature; °C

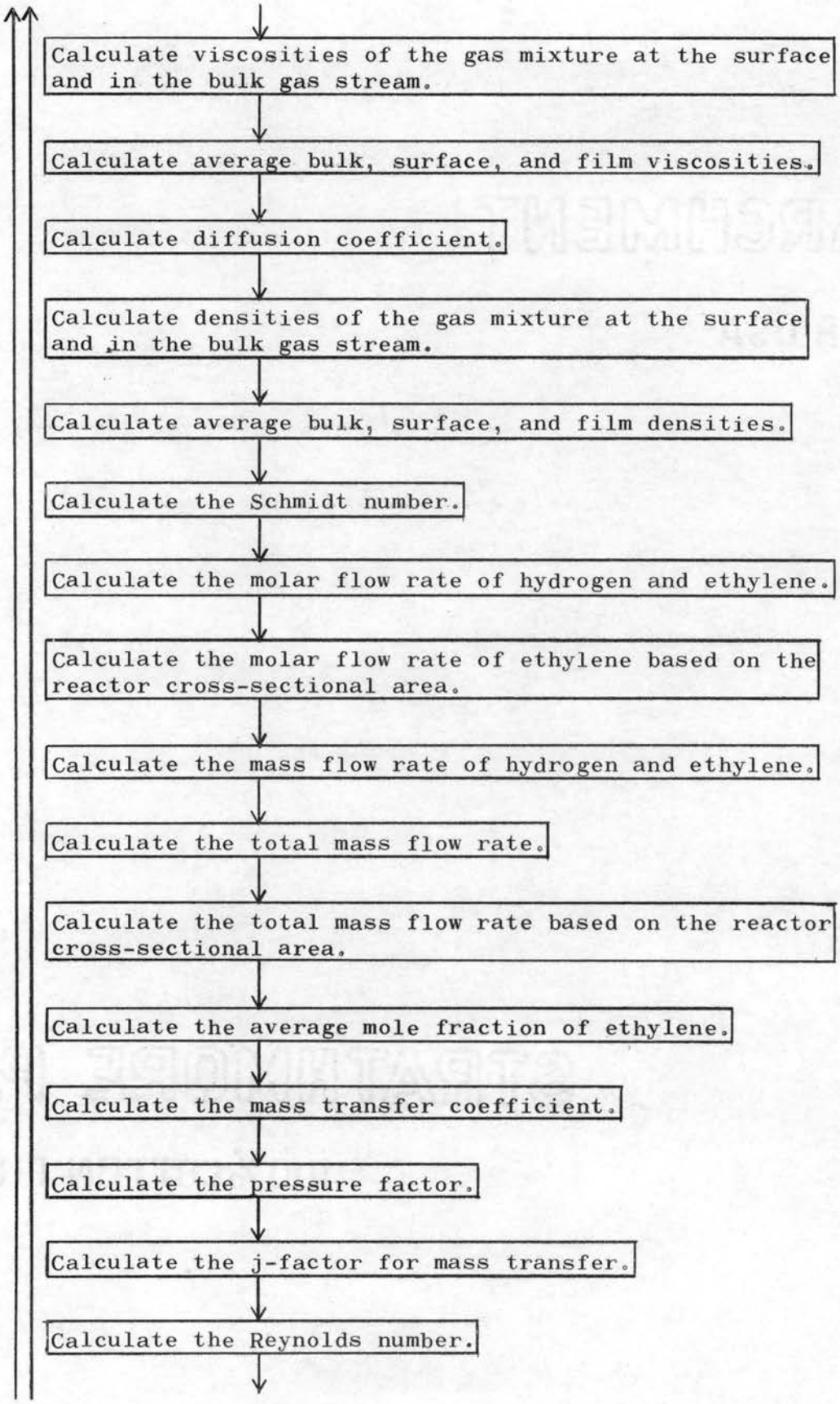
7. Average bulk temperature; °C

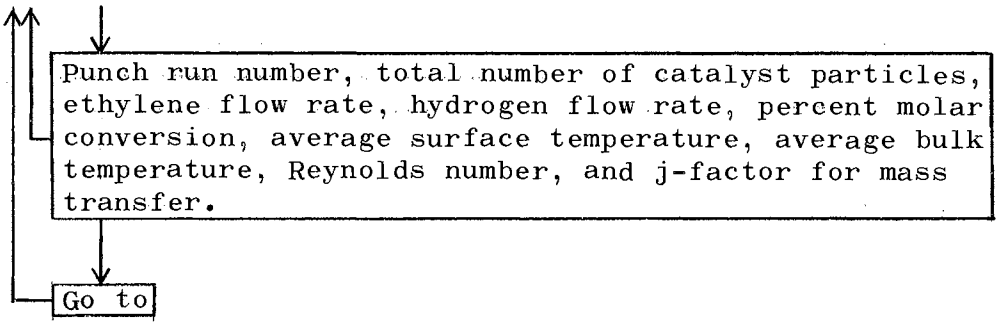
8. Reynolds number

9. j-factor for mass transfer

Block Diagram




Calculate viscosities of the gas mixture at the surface and in the bulk gas stream.
Calculate average bulk, surface, and film viscosities.
Calculate diffusion coefficient.
Calculate densities of the gas mixture at the surface and in the bulk gas stream.
Calculate average bulk, surface, and film densities.
Calculate the Schmidt number.
Calculate the molar flow rate of hydrogen and ethylene.
Calculate the molar flow rate of ethylene based on the reactor cross-sectional area.
Calculate the mass flow rate of hydrogen and ethylene.
Calculate the total mass flow rate.
Calculate the total mass flow rate based on the reactor cross-sectional area.
Calculate the average mole fraction of ethylene.
Calculate the mass transfer coefficient.
Calculate the pressure factor.
Calculate the j-factor for mass transfer.
Calculate the Reynolds number.


Punch run number, total number of catalyst particles, ethylene flow rate, hydrogen flow rate, percent molar conversion, average surface temperature, average bulk temperature, Reynolds number, and j-factor for mass transfer.
Go to

END

The list that follows contains the nomenclature used in the computer program for the calculation of j_D. The terms are listed in the order in which they appear in the program. Immediately following this list is a listing of the computer program.

Term	Description
NRUN	Run number
NPAR	Number of catalyst particles without thermocouples in bed
NTPAR	Number of catalyst particles with thermocouples in bed
NPTS	Number of data points in run
SURFA	Surface area of catalyst particles; cm^2
PARD	Catalyst particle diameter; cm
TUBD	Reaction tube diameter; cm
PHI	Shape factor for catalyst particles
NPART	Total number of catalyst particles
VMR	Potential of thermocouple used to measure room temperature; millivolts
VMB	Potential of thermocouples used to measure bulk gas temperature (1-bottom; 2-top); millivolts
VMS	Potential of thermocouples used to measure catalyst surface temperature (1-bottom; 2-top); millivolts
HFLO	Hydrogen volumetric flow rate; cc/sec
EEFLO	Ethylene volumetric flow rate; cc/sec
ARAT	Ratio of ethane peak area to ethylene peak area (from chromatograph chart; corrected for attenuation)
TR	Room temperature; °C
TB1	Bulk gas temperature at bottom of bed; °C
TB2	Bulk gas temperature at top of bed; °C
TS1	Catalyst surface temperature at bottom of bed; °C

Term	Description
TS2	Catalyst surface temperature at top of bed; °C
TB	Average bulk temperature; °C
TS	Average catalyst surface temperature; °C
TAV	Average film temperature; °C
VHB	Viscosity of hydrogen at bulk gas conditions (1-bottom; 2-top); gm/cm-sec
VEEB	Viscosity of ethylene at bulk gas conditions (1-bottom; 2-top); gm/cm-sec
VEAB	Viscosity of ethane at bulk gas conditions (1-bottom; 2-top); gm/cm-sec
VHS	Viscosity of hydrogen at catalyst surface conditions (1-bottom; 2-top); gm/cm-sec
FRH1	Mole fraction hydrogen in the entering bulk gas
FREE1	Mole fraction ethylene in the entering bulk gas
FREA1	Mole fraction ethane in the entering bulk gas
RATM	Mole ratio of ethane to ethylene in the exit bulk gas
X	Term used to calculate mole fractions in the exit bulk gas
FREA2	Mole fraction ethane in the exit bulk gas
FREE2	Mole fraction ethylene in the exit bulk gas
FRH2	Mole fraction hydrogen in the exit bulk gas
CON	Fraction molar conversion
PCCON	Percent molar conversion
VB1	Viscosity of bulk gas at bottom of bed; gm/cm-sec
VB2	Viscosity of bulk gas at top of bed; gm/cm-sec
VS1	Viscosity of gas at catalyst surface at bottom of bed; gm/cm-sec
VS2	Viscosity of gas at catalyst surface at top of bed; gm/cm-sec

Term	Description
VB	Average bulk viscosity; gm/cm-sec
VS	Average surface viscosity; gm/cm-sec
VAV	Average film viscosity; gm/cm-sec
DAB	Diffusion coefficient for diffusion of ethylene in hydrogen at average film conditions; cm^2/sec
RHOB1	Density of bulk gas at bottom of bed; gm/cm^3
RHOB2	Density of bulk gas at top of bed; gm/cm^3
RHOS1	Density of gas at catalyst surface at bottom of bed; gm/cm^3
RHOS2	Density of gas at catalyst surface at top of bed; gm/cm^3
RHOB	Average bulk density; gm/cm^3
RHOS	Average surface density; gm/cm^3
RHOAV	Average film density; gm/cm^3
SC	Schmidt number
GMH	Molar flow rate of hydrogen; gm mole/sec
GMEE	Molar flow rate of ethylene; gm mole/sec
GMEEX	Molar flow rate of ethylene based on reactor cross-section; gm $mole/cm^2$-sec
GH	Mass flow rate of hydrogen; gm/sec
GEE	Mass flow rate of ethylene; gm/sec
GT	Total mass flow rate; gm/sec
GMASS	Total mass flow rate based on reactor cross-section; gm/cm^2-sec
AVMF	Average mole fraction of ethylene in the bulk gas
COEF	Mass transfer coefficient based on transfer of ethylene; gm $mole/cm^2$-sec-atm
PF	Pressure factor; atm
FACJ	j-factor for mass transfer
RE	Reynolds number

```
C      BERRY CRAIN, JR.   CALCULATION OF JD-1620
 100   READ 10,NRUN,NPAR,NTPAR,NPTS
       READ 11,SURFA,PARD,TUBD,PHI
       NPART=NPAR+NTPAR
       DO 101 I=1,NPTS
       READ 12,VMR,VMB1,VMB2,VMS1,VMS2
       READ 13,HFLO,EEFLO,ARAT
       TR=4.20+18.14*VMR
       TB1=4.20+18.14*VMB1
       TB2=4.20+18.14*VMB2
       TS1=4.20+18.14*VMS1
       TS2=4.20+18.14*VMS2
       TB=(TB1+TB2)/2.0
       TS=(TS1+TS2)/2.0
       TAV=(TB+TS)/2.0
       VHB1=0.0000847+0.000000183*TB1
       VHB2=0.0000847+0.000000183*TB2
       VEEB1=0.0000956+0.0000002964*TB1
       VEEB2=0.0000956+0.0000002964*TB2
       VEAB1=0.0000859+0.000000275*TB1
       VEAB2=0.0000859+0.000000275*TB2
       VHS1=0.0000847+0.000000183*TS1
       VHS2=0.0000847+0.000000183*TS2
       FRH1=HFLO/(HFLO+EEFLO)
       FREE1=1.0-FRH1
       FREA1=0.0
       RATM=(28.05/30.07)*ARAT
       X=(0.2*RATM)/(1.0+RATM)
       FREA2=X/(1.0-X)
       FREE2=FREA2/RATM
       FRH2=1.0-FREA2-FREE2
       CON=X/0.2
       PCCON=CON*100.0
       VB1=FRH1*VHB1+FREE1*VEEB1
       VB2=FRH2*VHB2+FREE2*VEEB2+FREA2*VEAB2
       VS1=VHS1
       VS2=VHS2
       VB=(VB1+VB2)/2.0
       VS=(VS1+VS2)/2.0
       VAV=(VB+VS)/2.0
       DAB=0.0000185*(TAV+273.16)**1.823
       RHOB1=(0.01219/(TB1+273.16))*(FRH1*2.016+FREE1*28.05)
       RHOB2=(0.01219/(TB2+273.16))*(FRH2*2.016+FREE2*28.05+FREA2*30.07)
       RHOS1=(0.01219/(TS1+273.16))*2.016
       RHOS2=(0.01219/(TS2+273.16))*2.016
       RHOB=(RHOB1+RHOB2)/2.0
       RHOS=(RHOS1+RHOS2)/2.0
       RHOAV=(RHOB+RHOS)/2.0
       SC=VAV/(RHOAV*DAB)
       GMH=(HFLO*273.16)/(22410.0*(TR+273.16))
```

```
      GMEE=(EEFLO*273.16)/(22410.0*(TR+273.16))
      GMEEX=GMEE/(0.785*(TUBD)**2)
      GH=GMH*2.016
      GEE=GMEE*28.05
      GT=GH+GEE
      GMASS=GT/(0.785*(TUBD)**2)
      AVMF=(FREE1+FREE2)/2.0
      COEF=(GMEE*CON)/(SURFA*AVMF)
      PF=0.8
      FACJ=((COEF*PF)/GMEEX)*(SC)**0.66667
      RE=(PARD*GMASS)/(VAV*PHI)
  101 PUNCH 20,NRUN,NPART,EEFLO,HFLO,PCCON,TS,TB,RE,FACJ
      GO TO 100
   10 FORMAT (I5,I5,I5,I5)
   11 FORMAT (F10.1,F10.1,F10.1,F10.1)
   12 FORMAT (F10.1,F10.1,F10.1,F10.1,F10.1)
   13 FORMAT (F10.1,F10.1,F10.1)
   20 FORMAT (2X,I4,I4,F6.1,F7.1,F8.2,F8.1,F8.1,F8.3,F8.2)
      END
```

APPENDIX C

CURVE FIT PROGRAM

j-FACTOR vs. REYNOLDS NUMBER

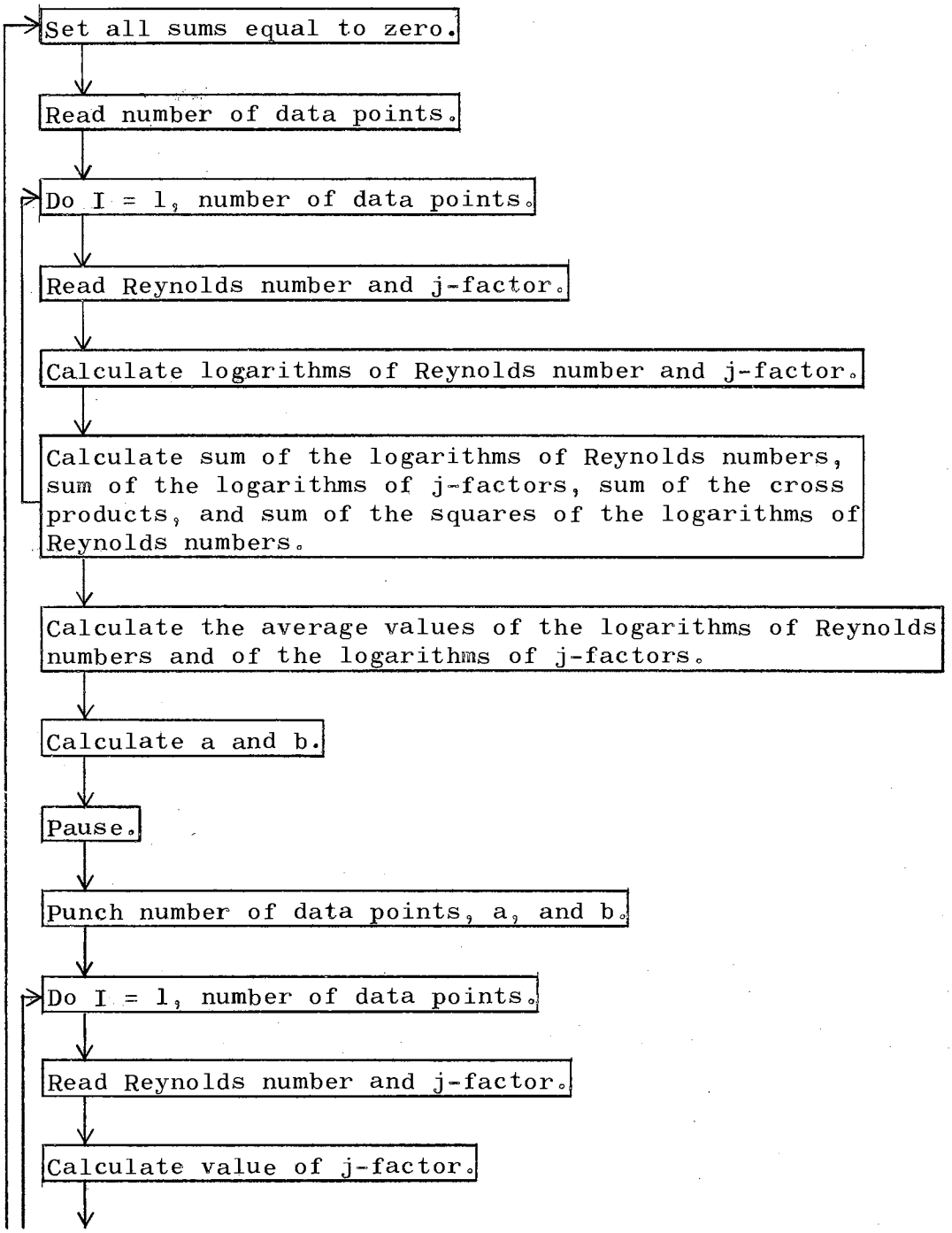
A FORTRAN program was written for the IBM 1620 Digital Computer to fit log j_D vs. log N_{Re} to a straight line. Using the method of least squares explained by Ostle (27), the program evaluated the coefficient and exponent of the equation, $j_D = a(N_{Re})^b$. The program calculated the percent deviation of each point as well as the standard estimate of error and the average percent deviation for all the points.

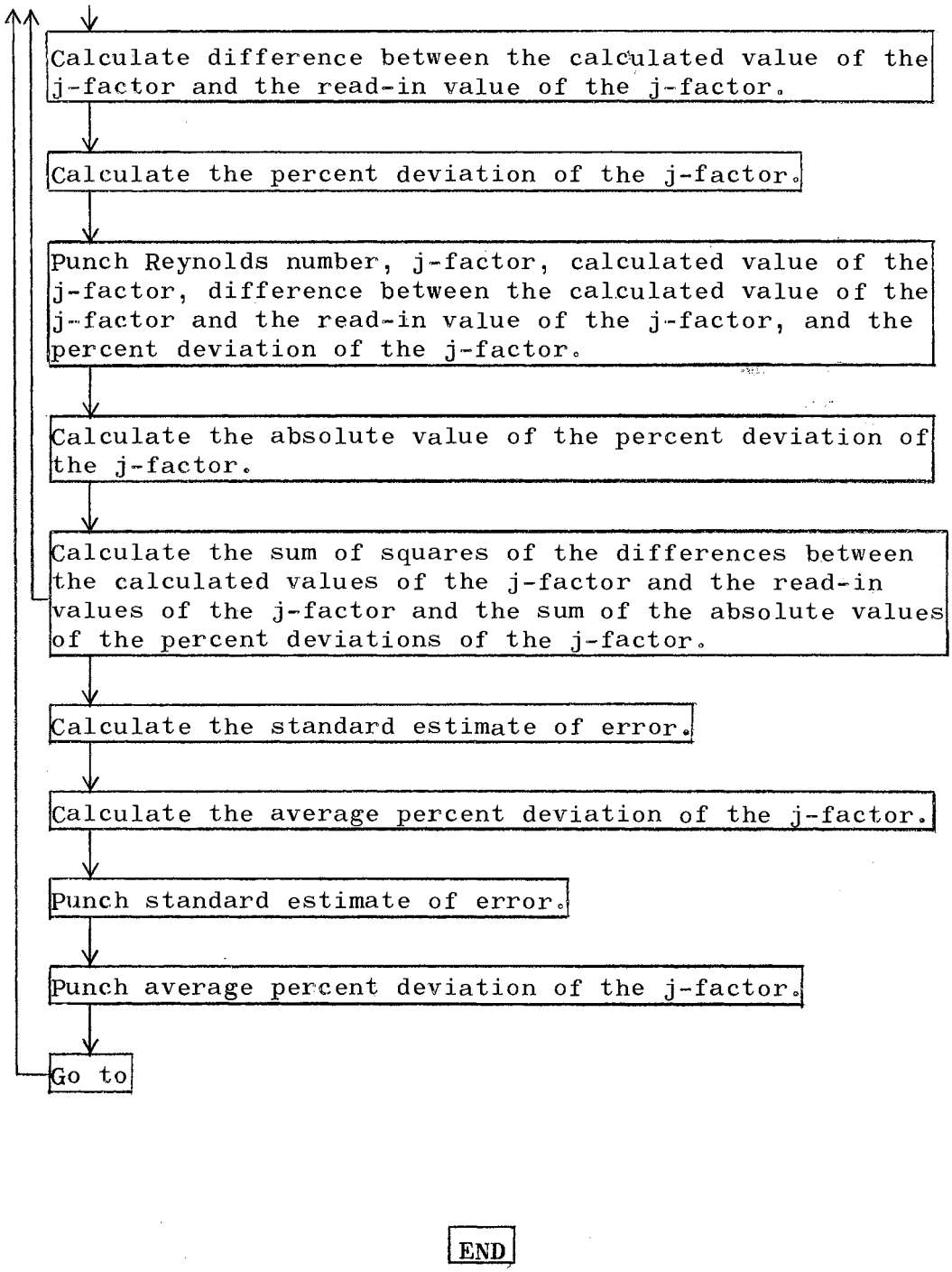
The input data for this program was the output data of the j_D-calculation program explained in Appendix B. Below is an explanation of the nomenclature used. A block diagram of the program appears on pages 57 and 58 followed by a listing of the program.

Term	Description
SX	Sum of the logarithms of the Reynolds numbers
SY	Sum of the logarithms of the j-factors
SXY	Sum of the cross products of the logarithms of the Reynolds numbers and the logarithms of the j-factors
SDIF2	Sum of squares of the differences, $j_{act} - j_{calc}$
SPC	Sum of the absolute values of the percent deviations
N	Number of data points

Term	Description
X	Reynolds number and logarithm of the Reynolds number
Y	j-factor and logarithm of the j-factor
Z	Number of data points
XAV	Average value of the logarithms of the Reynolds numbers
YAV	Average value of the logarithms of the j-factors
B	b in $j_D = a(N_{Re})^b$
A	Logarithm a and a in $j_D = a(N_{Re})^b$
YCAL	Value of the j-factor calculated from $j_D = a(N_{Re})^b$
DIF	$j_{act} - j_{calc}$
PCDIF	Percent deviation, $100 \times [(j_{act} - j_{calc})/j_{calc}]$
PCAB	Absolute value of the percent deviation
SEE	Standard estimate of error
AVPC	Average percent deviation

Block Diagram




Calculate difference between the calculated value of the j-factor and the read-in value of the j-factor.
Calculate the percent deviation of the j-factor.
Punch Reynolds number, j-factor, calculated value of the j-factor, difference between the calculated value of the j-factor and the read-in value of the j-factor, and the percent deviation of the j-factor.
Calculate the absolute value of the percent deviation of the j-factor.
Calculate the sum of squares of the differences between the calculated values of the j-factor and the read-in values of the j-factor and the sum of the absolute values of the percent deviations of the j-factor.
Calculate the standard estimate of error.
Calculate the average percent deviation of the j-factor.
Punch standard estimate of error.
Punch average percent deviation of the j-factor.
Go to
END

```
C     BERRY CRAIN, JR.   CURVE FIT OF JD VS. RE
 100  SX=0.0
      SY=0.0
      SXY=0.0
      SX2=0.0
      SDIF2=0.0
      SPC=0.0
      READ 10,N
      DO 101 I=1,N
      READ 11,X,Y
      X=LOGF(X)
      Y=LOGF(Y)
      SX=SX+X
      SY=SY+Y
      SXY=SXY+X*Y
 101  SX2=SX2+X**2
      Z=N
      XAV=SX/Z
      YAV=SY/Z
      B=(SXY-(SX*SY)/Z)/(SX2-((SX)**2)/Z)
      A=YAV-B*XAV
      A=EXPF(A)
      PAUSE
      PUNCH 20
      PUNCH 21,N,A,B
      PUNCH 22
      DO 102 I=1,N
      READ 11,X,Y
      YCAL=A*(X)**B
      DIF=Y-YCAL
      PCDIF=100.0*(DIF/YCAL)
      PUNCH 23,X,Y,YCAL,DIF,PCDIF
      PCAB=ABSF(PCDIF)
      SDIF2=SDIF2+(DIF)**2
 102  SPC=SPC+PCAB
      SEE=(SDIF2/(Z-2.0))**0.5
      AVPC=SPC/Z
      PUNCH 24,SEE
      PUNCH 25,AVPC
      GO TO 100
  10  FORMAT (I5)
  11  FORMAT (47X,F8.3,F8.2)
  20  FORMAT (22HCURVE FIT OF JD VS. RE//)
  21  FORMAT (13HNO. OF PTS. =,I5,4X,3HA =,F10.5,4X,3HB =,F10.7//)
  22  FORMAT (8X,1HX,13X,1HY,11X,5HYCALC,10X,3HDIF,10X,5HPCDIF/)
  23  FORMAT (E14.6,E14.6,E14.6,E14.6,E14.6)
  24  FORMAT (/19HST. EST. OF ERROR =,E13.6/)
  25  FORMAT (16HAV. PCT. DIFF. =,E13.6)
      END
```

APPENDIX D

EXPERIMENTAL AND CALCULATED DATA

RUN NO	NO OF PAR	ETHYL ENE CC/SC	HYDRO GEN CC/SC	CON VER SION	SURF TEMP C	BULK TEMP C	REYNOLDS NUMBER	J FAC
131	9	.5	2.0	78.23	121.3	97.3	.260	8.33
131	9	.5	2.0	78.23	120.6	96.6	.261	8.33
131	9	.5	2.0	78.23	120.7	96.5	.261	8.33
131	9	1.0	4.0	59.12	133.8	96.4	.515	5.43
131	9	1.0	4.0	59.12	133.7	96.0	.516	5.43
131	9	1.5	6.0	50.45	142.5	95.8	.768	4.37
131	9	1.5	6.0	50.45	142.3	95.6	.768	4.37
131	9	2.0	8.0	44.27	150.7	97.1	1.016	3.69
131	9	2.0	8.0	44.27	150.6	97.0	1.016	3.69
131	9	2.5	10.0	40.80	156.3	96.8	1.264	3.33
131	9	2.5	10.0	40.80	156.3	97.0	1.264	3.33
131	9	3.0	12.0	36.86	159.9	97.2	1.511	2.94
131	9	3.0	12.0	36.86	160.2	97.1	1.511	2.94
131	9	3.5	14.0	35.19	166.6	97.3	1.753	2.77
131	9	3.5	14.0	35.19	166.4	97.2	1.754	2.77
131	9	4.0	16.0	32.84	171.7	97.3	1.995	2.55
131	9	4.0	16.0	32.84	171.9	97.3	1.995	2.55
131	9	4.5	18.0	32.84	175.5	97.3	2.238	2.54
131	9	4.5	18.0	32.84	176.1	97.3	2.237	2.54
131	9	5.0	20.0	30.49	179.4	97.6	2.478	2.33
131	9	5.0	20.0	30.49	179.9	97.9	2.476	2.33
131	9	5.5	22.0	28.84	183.7	98.2	2.714	2.18
131	9	5.5	22.0	28.84	183.7	98.3	2.714	2.18
132	9	.5	2.0	78.02	121.3	97.3	.260	8.29
132	9	.5	2.0	78.02	120.6	96.6	.260	8.30
132	9	.5	2.0	78.02	120.7	96.5	.260	8.29
132	9	1.0	4.0	59.52	133.8	96.4	.515	5.48
132	9	1.0	4.0	59.52	133.7	96.0	.515	5.48
132	9	1.5	6.0	52.36	142.5	95.8	.767	4.59
132	9	1.5	6.0	52.36	142.3	95.6	.767	4.59
132	9	2.0	8.0	44.76	150.7	97.1	1.014	3.74
132	9	2.0	8.0	44.76	150.6	97.0	1.014	3.74
132	9	2.5	10.0	40.11	156.3	96.8	1.261	3.26
132	9	2.5	10.0	40.11	156.3	97.0	1.261	3.26
132	9	3.0	12.0	36.95	159.9	97.2	1.509	2.95
132	9	3.0	12.0	36.95	160.2	97.1	1.508	2.95
132	9	3.5	14.0	34.50	166.6	97.3	1.750	2.71
132	9	3.5	14.0	34.50	166.4	97.2	1.751	2.71
132	9	4.0	16.0	33.23	171.7	97.3	1.992	2.58
132	9	4.0	16.0	33.23	171.9	97.3	1.991	2.58
132	9	4.5	18.0	31.66	175.5	97.3	2.234	2.44
132	9	4.5	18.0	31.66	176.1	97.3	2.233	2.44
132	9	5.0	20.0	30.30	179.4	97.6	2.473	2.31
132	9	5.0	20.0	30.30	179.9	97.9	2.472	2.31
132	9	5.5	22.0	29.13	183.7	98.2	2.710	2.20
132	9	5.5	22.0	29.13	183.7	98.3	2.709	2.20

RUN NO	NO OF PAR	ETHYL ENE CC/SC	HYDRO GEN CC/SC	CON VER SION	SURF TEMP C	BULK TEMP C	REYNOLDS NUMBER	J FAC
133	9	.5	2.0	78.12	121.3	97.3	.260	8.31
133	9	.5	2.0	78.12	120.6	96.6	.260	8.31
133	9	.5	2.0	78.12	120.7	96.5	.260	8.31
133	9	1.0	4.0	59.83	133.8	96.4	.514	5.52
133	9	1.0	4.0	59.83	133.7	96.0	.514	5.52
133	9	1.5	6.0	50.25	142.5	95.8	.766	4.35
133	9	1.5	6.0	50.25	142.3	95.6	.766	4.35
133	9	2.0	8.0	44.27	150.7	97.1	1.013	3.69
133	9	2.0	8.0	44.27	150.6	97.0	1.013	3.69
133	9	2.5	10.0	40.40	156.3	96.8	1.260	3.29
133	9	2.5	10.0	40.40	156.3	97.0	1.260	3.29
133	9	3.0	12.0	36.56	159.9	97.2	1.507	2.91
133	9	3.0	12.0	36.56	160.2	97.1	1.507	2.91
133	9	3.5	14.0	34.50	166.6	97.3	1.749	2.71
133	9	3.5	14.0	34.50	166.4	97.2	1.749	2.71
133	9	4.0	16.0	32.84	171.7	97.3	1.990	2.55
133	9	4.0	16.0	32.84	171.9	97.3	1.990	2.55
133	9	4.5	18.0	31.57	175.5	97.3	2.231	2.43
133	9	4.5	18.0	31.57	176.1	97.3	2.230	2.43
133	9	5.0	20.0	29.91	179.4	97.6	2.471	2.28
133	9	5.0	20.0	29.91	179.9	97.9	2.469	2.28
133	9	5.5	22.0	28.45	183.7	98.2	2.707	2.15
133	9	5.5	22.0	28.45	183.7	98.3	2.707	2.15
134	9	.5	2.0	78.43	121.3	97.3	.259	8.37
134	9	.5	2.0	78.43	120.6	96.6	.259	8.37
134	9	.5	2.0	78.43	120.7	96.5	.259	8.37
134	9	1.5	6.0	49.65	142.5	95.8	.764	4.28
134	9	1.5	6.0	49.65	142.3	95.6	.765	4.28
134	9	2.0	8.0	44.76	150.7	97.1	1.011	3.74
134	9	2.0	8.0	44.76	150.6	97.0	1.011	3.74
134	9	2.5	10.0	37.74	156.3	96.8	1.258	3.03
134	9	2.5	10.0	37.74	156.3	97.0	1.258	3.03
134	9	3.0	12.0	36.76	159.9	97.2	1.505	2.93
134	9	3.0	12.0	36.76	160.2	97.1	1.504	2.93
134	9	3.5	14.0	34.89	166.6	97.3	1.745	2.74
134	9	3.5	14.0	34.89	166.4	97.2	1.746	2.74
134	9	4.5	18.0	31.47	175.5	97.3	2.227	2.42
134	9	4.5	18.0	31.47	176.1	97.3	2.226	2.42
134	9	5.0	20.0	30.01	179.4	97.6	2.466	2.29
134	9	5.0	20.0	30.01	179.9	97.9	2.465	2.29
135	9	.5	2.0	78.20	121.3	97.3	.259	8.33
135	9	.5	2.0	78.20	120.6	96.6	.259	8.33
135	9	.5	2.0	78.20	120.7	96.5	.259	8.33
135	9	1.0	4.0	59.49	133.8	96.4	.513	5.48
135	9	1.0	4.0	59.49	133.7	96.0	.513	5.48
135	9	1.5	6.0	50.68	142.5	95.8	.764	4.40

RUN NO	NO OF PAR	ETHYL ENE CC/SC	HYDRO GEN CC/SC	CON VER SION	SURF TEMP C	BULK TEMP C	REYNOLDS NUMBER	J FAC
135	9	1.5	6.0	50.68	142.3	95.6	.764	4.40
135	9	2.0	8.0	44.54	150.7	97.1	1.010	3.72
135	9	2.0	8.0	44.54	150.6	97.0	1.010	3.72
135	9	2.5	10.0	40.01	156.3	96.8	1.257	3.25
135	9	2.5	10.0	40.01	156.3	97.0	1.257	3.25
135	9	3.0	12.0	36.78	159.9	97.2	1.503	2.93
135	9	3.0	12.0	36.78	160.2	97.1	1.503	2.93
135	9	3.5	14.0	34.77	166.6	97.3	1.744	2.73
135	9	3.5	14.0	34.77	166.4	97.2	1.744	2.73
135	9	4.0	16.0	32.97	171.7	97.3	1.984	2.56
135	9	4.0	16.0	32.97	171.9	97.3	1.984	2.56
135	9	4.5	18.0	32.86	175.5	97.3	2.226	2.54
135	9	4.5	18.0	32.86	176.1	97.3	2.225	2.54
135	9	5.0	20.0	30.18	179.4	97.6	2.464	2.30
135	9	5.0	20.0	30.18	179.9	97.9	2.463	2.30
135	9	5.5	22.0	28.81	183.7	98.2	2.700	2.18
135	9	5.5	22.0	28.81	183.7	98.3	2.699	2.18
141	9	.5	2.0	72.32	90.6	68.0	.276	7.40
141	9	.5	2.0	72.32	90.2	67.3	.276	7.40
141	9	1.5	6.0	44.37	112.6	68.0	.810	3.74
141	9	1.5	6.0	44.37	112.6	68.2	.810	3.74
141	9	2.5	10.0	37.84	126.5	67.9	1.334	3.05
141	9	2.5	10.0	37.84	126.5	68.0	1.334	3.05
141	9	3.5	14.0	36.17	137.8	68.1	1.849	2.87
141	9	3.5	14.0	36.17	137.6	68.1	1.850	2.87
141	9	4.5	18.0	30.79	146.7	68.0	2.359	2.36
141	9	4.5	18.0	30.79	146.8	68.0	2.359	2.36
141	9	5.5	22.0	29.23	153.4	68.0	2.867	2.22
141	9	5.5	22.0	29.23	152.6	67.9	2.869	2.22
142	9	.5	2.0	72.63	90.6	68.0	.275	7.45
142	9	.5	2.0	72.63	90.2	67.3	.275	7.45
142	9	1.5	6.0	47.45	112.6	68.0	.809	4.07
142	9	1.5	6.0	47.45	112.6	68.2	.809	4.07
142	9	2.5	10.0	38.73	126.5	67.9	1.332	3.14
142	9	2.5	10.0	38.73	126.5	68.0	1.332	3.14
142	9	3.5	14.0	33.62	137.8	68.1	1.846	2.63
142	9	3.5	14.0	33.62	137.6	68.1	1.846	2.63
142	9	4.5	18.0	30.69	146.7	68.0	2.355	2.35
142	9	4.5	18.0	30.69	146.8	68.0	2.354	2.35
142	9	5.5	22.0	28.94	153.4	68.0	2.862	2.19
142	9	5.5	22.0	28.94	152.6	67.9	2.864	2.19
143	9	.5	2.0	72.32	90.6	68.0	.275	7.40
143	9	.5	2.0	72.32	90.2	67.3	.275	7.40
143	9	1.5	6.0	47.05	112.6	68.0	.808	4.02
143	9	1.5	6.0	47.05	112.6	68.2	.808	4.02
143	9	2.5	10.0	37.94	126.5	67.9	1.330	3.06

RUN NO	NO OF PAR	ETHYL ENE CC/SC	HYDRO GEN CC/SC	CON VER SION	SURF TEMP C	BULK TEMP C	REYNOLDS NUMBER	J FAC
143	9	2.5	10.0	37.94	126.5	68.0	1.330	3.06
143	9	3.5	14.0	34.40	137.8	68.1	1.844	2.70
143	9	3.5	14.0	34.40	137.6	68.1	1.844	2.70
143	9	4.5	18.0	30.30	146.7	68.0	2.352	2.32
143	9	4.5	18.0	30.30	146.8	68.0	2.352	2.32
143	9	5.5	22.0	31.66	153.4	68.0	2.859	2.43
143	9	5.5	22.0	31.66	152.6	67.9	2.861	2.43
144	9	.5	2.0	72.42	90.6	68.0	.274	7.42
144	9	.5	2.0	72.42	90.2	67.3	.275	7.42
144	9	1.5	6.0	47.35	112.6	68.0	.807	4.06
144	9	1.5	6.0	47.35	112.6	68.2	.807	4.06
144	9	2.5	10.0	38.13	126.5	67.9	1.328	3.08
144	9	2.5	10.0	38.13	126.5	68.0	1.328	3.08
144	9	3.5	14.0	34.01	137.8	68.1	1.841	2.67
144	9	3.5	14.0	34.01	137.6	68.1	1.841	2.67
144	9	4.5	18.0	30.49	146.7	68.0	2.348	2.34
144	9	4.5	18.0	30.49	146.8	68.0	2.348	2.34
145	9	.5	2.0	73.14	90.6	68.0	.274	7.53
145	9	.5	2.0	73.14	90.2	67.3	.274	7.53
145	9	.5	2.0	72.57	90.6	68.0	.274	7.44
145	9	.5	2.0	72.57	90.2	67.3	.274	7.44
145	9	1.5	6.0	46.55	112.6	68.0	.806	3.97
145	9	1.5	6.0	46.55	112.6	68.2	.806	3.97
145	9	2.5	10.0	38.16	126.5	67.9	1.327	3.08
145	9	2.5	10.0	38.16	126.5	68.0	1.327	3.08
145	9	3.5	14.0	34.55	137.8	68.1	1.839	2.72
145	9	3.5	14.0	34.55	137.6	68.1	1.839	2.72
145	9	4.5	18.0	30.57	146.7	68.0	2.346	2.34
145	9	4.5	18.0	30.57	146.8	68.0	2.346	2.34
145	9	5.5	22.0	29.94	153.4	68.0	2.851	2.28
145	9	5.5	22.0	29.94	152.6	67.9	2.853	2.28
151	9	1.0	4.0	59.42	133.8	96.2	.517	5.47
151	9	1.0	4.0	59.42	133.8	96.3	.517	5.47
151	9	2.0	8.0	44.56	150.7	97.0	1.019	3.72
151	9	2.0	8.0	44.56	150.8	97.1	1.019	3.72
151	9	5.0	20.0	30.20	179.5	97.7	2.486	2.30
151	9	5.0	20.0	30.20	179.6	97.9	2.486	2.30
152	9	1.0	4.0	59.22	133.8	96.2	.517	5.45
152	9	1.0	4.0	59.22	133.8	96.3	.517	5.45
152	9	2.0	8.0	44.27	150.7	97.0	1.018	3.69
152	9	2.0	8.0	44.27	150.8	97.1	1.017	3.69
152	9	5.0	20.0	29.91	179.5	97.7	2.482	2.28
152	9	5.0	20.0	29.91	179.6	97.9	2.481	2.28
153	9	1.0	4.0	59.63	133.8	96.2	.517	5.50
153	9	1.0	4.0	59.63	133.8	96.3	.517	5.50
153	9	2.0	8.0	44.47	150.7	97.0	1.018	3.71

RUN NO	NO OF PAR	ETHYL ENE CC/SC	HYDRO GEN CC/SC	CON VER SION	SURF TEMP C	BULK TEMP C	REYNOLDS NUMBER	J FAC
153	9	2.0	8.0	44.47	149.4	97.1	1.019	3.71
153	9	5.0	20.0	30.10	179.5	97.7	2.482	2.29
153	9	5.0	20.0	30.10	179.6	97.9	2.481	2.29
154	9	1.0	4.0	59.52	133.8	96.2	.516	5.48
154	9	1.0	4.0	59.52	133.8	96.3	.516	5.48
154	9	2.0	8.0	44.66	150.7	97.0	1.017	3.73
154	9	2.0	8.0	44.66	150.8	97.1	1.017	3.73
154	9	5.0	20.0	30.01	179.5	97.7	2.480	2.29
154	9	5.0	20.0	30.01	179.6	97.9	2.479	2.29
155	9	1.0	4.0	59.45	133.8	96.2	.516	5.48
155	9	1.0	4.0	59.45	133.8	96.3	.516	5.48
155	9	2.0	8.0	44.49	150.7	97.0	1.016	3.71
155	9	2.0	8.0	44.49	150.8	97.1	1.016	3.71
155	9	5.0	20.0	30.06	179.5	97.7	2.477	2.29
155	9	5.0	20.0	30.06	179.6	97.9	2.477	2.29
181	3	1.0	4.0	18.86	123.1	93.4	.516	4.26
181	3	1.0	4.0	18.86	123.5	93.2	.516	4.26
181	3	1.0	4.0	18.86	123.8	93.2	.516	4.26
181	3	1.5	6.0	13.52	132.7	94.0	.768	2.97
181	3	1.5	6.0	13.52	132.9	94.1	.767	2.97
181	3	1.5	6.0	13.52	131.5	93.7	.769	2.97
181	3	2.0	8.0	13.53	138.5	94.2	1.018	2.96
181	3	2.0	8.0	13.53	138.7	94.1	1.018	2.96
181	3	2.0	8.0	13.53	138.7	94.3	1.018	2.96
181	3	2.5	10.0	11.96	143.2	94.6	1.267	2.59
181	3	2.5	10.0	11.96	143.6	94.9	1.267	2.59
181	3	2.5	10.0	11.96	143.9	94.8	1.266	2.59
181	3	3.5	14.0	10.73	152.8	95.2	1.759	2.30
181	3	3.5	14.0	10.73	153.0	95.3	1.759	2.30
181	3	3.5	14.0	10.73	156.1	95.6	1.754	2.30
181	3	4.5	18.0	9.12	159.8	95.1	2.249	1.93
181	3	4.5	18.0	9.12	160.0	95.0	2.249	1.93
181	3	4.5	18.0	9.12	159.9	94.8	2.250	1.93
181	3	5.5	22.0	8.15	167.9	94.8	2.731	1.71
181	3	5.5	22.0	8.15	167.6	94.8	2.732	1.71
181	3	5.5	22.0	8.15	168.0	95.0	2.731	1.71
182	3	1.0	4.0	18.85	123.1	93.4	.516	4.26
182	3	1.0	4.0	18.85	123.5	93.2	.516	4.26
182	3	1.0	4.0	18.85	123.8	93.2	.516	4.26
182	3	1.5	6.0	15.08	132.7	94.1	.768	3.33
182	3	1.5	6.0	15.08	132.9	94.1	.767	3.33
182	3	1.5	6.0	15.08	131.5	93.7	.769	3.34
182	3	2.0	8.0	13.21	138.5	94.2	1.018	2.89
182	3	2.0	8.0	13.21	138.7	94.1	1.018	2.89
182	3	2.0	8.0	13.21	138.7	94.3	1.018	2.89
182	3	2.5	10.0	12.89	143.2	94.6	1.268	2.81

RUN NO	NO OF PAR	ETHYL ENE CC/SC	HYDRO GEN CC/SC	CON VER SION	SURF TEMP C	BULK TEMP C	REYNOLDS NUMBER	J FAC
182	3	2.5	10.0	12.89	143.6	94.9	1.267	2.81
182	3	2.5	10.0	12.89	143.9	94.8	1.267	2.80
182	3	3.5	14.0	10.52	152.8	95.2	1.759	2.25
182	3	3.5	14.0	10.52	153.0	95.3	1.759	2.25
182	3	3.5	14.0	10.52	156.1	95.6	1.754	2.25
182	3	4.5	18.0	8.66	159.8	95.1	2.249	1.83
182	3	4.5	18.0	8.66	160.0	95.0	2.249	1.83
182	3	4.5	18.0	8.66	159.9	94.8	2.250	1.83
182	3	5.5	22.0	7.64	167.9	94.8	2.731	1.60
182	3	5.5	22.0	7.64	167.6	94.8	2.732	1.60
182	3	5.5	22.0	7.64	168.0	95.0	2.731	1.60
183	3	1.0	4.0	19.22	123.1	93.4	.517	4.35
183	3	1.0	4.0	19.22	123.5	93.2	.517	4.35
183	3	1.0	4.0	19.22	123.8	93.2	.516	4.35
183	3	1.5	6.0	15.28	132.7	94.1	.768	3.38
183	3	1.5	6.0	15.28	132.9	94.1	.768	3.38
183	3	1.5	6.0	15.28	131.5	93.7	.769	3.38
183	3	2.0	8.0	13.38	138.5	94.2	1.019	2.93
183	3	2.0	8.0	13.38	138.7	94.1	1.019	2.93
183	3	2.0	8.0	13.38	138.7	94.3	1.019	2.93
183	3	2.5	10.0	12.24	143.2	94.6	1.269	2.66
183	3	2.5	10.0	12.24	143.6	94.9	1.268	2.66
183	3	2.5	10.0	12.24	143.9	94.8	1.268	2.66
183	3	3.5	14.0	9.47	152.8	95.2	1.761	2.02
183	3	3.5	14.0	9.47	153.0	95.3	1.760	2.02
183	3	3.5	14.0	9.47	156.1	95.6	1.756	2.02
183	3	4.5	18.0	8.91	159.8	95.1	2.251	1.89
183	3	4.5	18.0	8.91	160.0	95.0	2.251	1.89
183	3	4.5	18.0	8.91	159.9	94.8	2.252	1.89
183	3	5.5	22.0	7.67	167.9	94.8	2.734	1.61
183	3	5.5	22.0	7.67	167.6	94.8	2.735	1.61
183	3	5.5	22.0	7.67	168.0	95.0	2.733	1.61
184	3	1.0	4.0	19.23	123.1	93.4	.517	4.35
184	3	1.0	4.0	19.23	123.5	93.2	.517	4.35
184	3	1.0	4.0	19.23	123.8	93.2	.517	4.35
184	3	1.5	6.0	15.54	132.7	94.1	.769	3.44
184	3	1.5	6.0	15.54	132.9	94.1	.769	3.44
184	3	1.5	6.0	15.54	131.5	93.7	.770	3.44
184	3	2.0	8.0	13.38	138.5	94.2	1.020	2.93
184	3	2.0	8.0	13.38	138.7	94.1	1.020	2.93
184	3	2.0	8.0	13.38	138.7	94.3	1.020	2.93
184	3	2.5	10.0	12.33	143.2	94.6	1.270	2.68
184	3	2.5	10.0	12.33	143.6	94.9	1.269	2.68
184	3	2.5	10.0	12.33	143.9	94.8	1.269	2.68
184	3	4.5	18.0	8.83	159.8	95.1	2.253	1.87
184	3	4.5	18.0	8.83	160.0	95.0	2.253	1.87

RUN NO	NO OF PAR	ETHYLENE CC/SC	HYDROGEN CC/SC	CONVERSION	SURF TEMP C	BULK TEMP C	REYNOLDS NUMBER	J FAC
184	3	4.5	18.0	8.83	159.9	94.8	2.254	1.87
184	3	5.5	22.0	7.97	167.9	94.8	2.736	1.67
184	3	5.5	22.0	7.97	167.6	94.8	2.737	1.67
184	3	5.5	22.0	7.97	168.0	95.0	2.736	1.67
185	3	1.0	4.0	19.05	123.1	93.4	.518	4.31
185	3	1.0	4.0	19.05	123.5	93.2	.518	4.31
185	3	1.0	4.0	19.05	123.8	93.2	.518	4.30
185	3	1.5	6.0	14.85	132.7	94.1	.770	3.28
185	3	1.5	6.0	14.85	132.9	94.1	.770	3.28
185	3	1.5	6.0	14.85	131.5	93.7	.771	3.28
185	3	2.0	8.0	13.37	138.5	94.2	1.022	2.92
185	3	2.0	8.0	13.37	138.7	94.1	1.022	2.92
185	3	2.0	8.0	13.37	138.7	94.3	1.022	2.92
185	3	2.5	10.0	12.33	143.2	94.6	1.272	2.68
185	3	2.5	10.0	12.33	143.6	94.9	1.271	2.68
185	3	2.5	10.0	12.33	143.9	94.8	1.271	2.68
185	3	3.5	14.0	10.28	152.8	95.2	1.766	2.20
185	3	3.5	14.0	10.28	153.0	95.3	1.765	2.20
185	3	3.5	14.0	10.28	156.1	95.6	1.760	2.20
185	3	4.5	18.0	8.88	159.8	95.1	2.257	1.88
185	3	4.5	18.0	8.88	160.0	95.0	2.257	1.88
185	3	4.5	18.0	8.88	159.9	94.8	2.258	1.88
185	3	5.5	22.0	7.86	167.9	94.8	2.741	1.65
185	3	5.5	22.0	7.86	167.6	94.8	2.742	1.65
185	3	5.5	22.0	7.86	168.0	95.0	2.741	1.65
191	3	1.0	4.0	17.27	94.9	64.2	.550	3.90
191	3	1.0	4.0	17.25	94.2	64.1	.550	3.89
191	3	1.0	4.0	17.25	94.3	64.3	.550	3.89
191	3	1.0	4.0	17.25	94.6	64.5	.550	3.89
191	3	1.5	6.0	13.86	101.7	64.2	.820	3.07
191	3	1.5	6.0	13.86	101.7	64.2	.820	3.07
191	3	1.5	6.0	13.86	101.8	64.3	.819	3.07
191	3	1.5	6.0	13.86	102.0	64.4	.819	3.07
191	3	2.0	8.0	12.19	107.3	64.0	1.088	2.67
191	3	2.0	8.0	12.19	106.9	63.6	1.088	2.67
191	3	2.0	8.0	12.19	106.6	63.2	1.089	2.67
191	3	2.0	8.0	12.19	106.3	63.1	1.090	2.67
191	3	2.5	10.0	11.16	112.0	63.6	1.355	2.42
191	3	2.5	10.0	11.16	112.0	63.5	1.355	2.42
191	3	2.5	10.0	11.16	112.0	63.6	1.354	2.42
191	3	2.5	10.0	11.16	112.0	63.5	1.355	2.42
191	3	3.5	14.0	9.49	121.4	63.7	1.880	2.03
191	3	3.5	14.0	9.49	121.8	63.7	1.880	2.03
191	3	3.5	14.0	9.49	121.6	63.7	1.880	2.03
191	3	3.5	14.0	9.49	121.1	63.6	1.881	2.03
191	3	4.5	18.0	8.63	128.9	63.8	2.401	1.83

RUN NO	NO OF PAR	ETHYL ENE CC/SC	HYDRO GEN CC/SC	CON VER SION	SURF TEMP C	BULK TEMP C	REYNOLDS NUMBER	J FAC
191	3	4.5	18.0	8.63	128.6	63.8	2.402	1.83
191	3	4.5	18.0	8.63	128.8	63.7	2.402	1.83
191	3	4.5	18.0	8.63	128.8	63.6	2.402	1.83
191	3	5.5	22.0	7.78	136.7	63.8	2.915	1.64
191	3	5.5	22.0	7.78	136.8	63.7	2.915	1.64
191	3	5.5	22.0	7.78	137.1	63.8	2.914	1.64
191	3	5.5	22.0	7.78	136.8	63.8	2.915	1.64
192	3	1.0	4.0	17.19	94.9	64.2	.548	3.88
192	3	1.0	4.0	17.19	94.2	64.1	.549	3.88
192	3	1.0	4.0	17.19	94.3	64.3	.548	3.88
192	3	1.0	4.0	17.19	94.6	64.5	.548	3.88
192	3	1.5	6.0	14.29	101.7	64.2	.817	3.17
192	3	1.5	6.0	14.29	101.7	64.2	.817	3.17
192	3	1.5	6.0	14.29	101.8	64.3	.817	3.17
192	3	1.5	6.0	14.29	102.0	64.4	.817	3.17
192	3	2.0	8.0	12.24	107.3	64.0	1.085	2.68
192	3	2.0	8.0	12.24	106.9	63.6	1.086	2.68
192	3	2.0	8.0	12.24	106.6	63.2	1.086	2.68
192	3	2.0	8.0	12.24	106.3	63.1	1.087	2.68
192	3	2.5	10.0	10.80	112.0	63.6	1.351	2.34
192	3	2.5	10.0	10.80	112.0	63.5	1.351	2.34
192	3	2.5	10.0	10.80	112.0	63.6	1.351	2.34
192	3	2.5	10.0	10.80	112.0	63.5	1.351	2.34
192	3	3.5	14.0	9.67	121.4	63.7	1.875	2.07
192	3	3.5	14.0	9.67	121.8	63.7	1.874	2.07
192	3	3.5	14.0	9.67	121.6	63.7	1.875	2.07
192	3	3.5	14.0	9.67	121.1	63.6	1.876	2.07
192	3	4.5	18.0	8.13	128.9	63.8	2.395	1.72
192	3	4.5	18.0	8.13	128.6	63.8	2.396	1.72
192	3	4.5	18.0	8.13	128.8	63.7	2.395	1.72
192	3	4.5	18.0	8.13	128.8	63.6	2.396	1.72
192	3	5.5	22.0	8.55	136.7	63.8	2.907	1.81
192	3	5.5	22.0	8.55	136.8	63.7	2.907	1.80
192	3	5.5	22.0	8.55	137.1	63.8	2.906	1.80
192	3	5.5	22.0	8.55	136.8	63.8	2.907	1.80
193	3	1.0	4.0	17.33	94.9	64.2	.547	3.91
193	3	1.0	4.0	17.33	94.2	64.1	.547	3.91
193	3	1.0	4.0	17.33	94.3	64.3	.547	3.91
193	3	1.0	4.0	17.33	94.6	64.5	.547	3.91
193	3	1.5	6.0	14.16	101.7	64.2	.815	3.14
193	3	1.5	6.0	14.16	101.7	64.2	.815	3.14
193	3	1.5	6.0	14.16	101.8	64.3	.815	3.14
193	3	1.5	6.0	14.16	102.0	64.4	.815	3.14
193	3	2.0	8.0	12.50	107.3	64.0	1.082	2.74
193	3	2.0	8.0	12.50	106.9	63.6	1.083	2.74
193	3	2.0	8.0	12.50	106.6	63.2	1.083	2.74

RUN NO	NO OF PAR	ETHYL ENE CC/SC	HYDRO GEN CC/SC	CON VER SION	SURF TEMP C	BULK TEMP C	REYNOLDS NUMBER	J FAC
193	3	2.0	8.0	12.50	106.3	63.1	1.084	2.74
193	3	2.5	10.0	10.97	112.0	63.6	1.347	2.38
193	3	2.5	10.0	10.97	112.0	63.5	1.347	2.38
193	3	2.5	10.0	10.97	112.0	63.6	1.347	2.38
193	3	2.5	10.0	10.97	112.0	63.5	1.347	2.38
193	3	3.5	14.0	9.34	121.4	63.7	1.870	2.00
193	3	3.5	14.0	9.34	121.8	63.7	1.869	2.00
193	3	3.5	14.0	9.34	121.6	63.7	1.870	2.00
193	3	3.5	14.0	9.34	121.1	63.6	1.871	2.00
193	3	4.5	18.0	8.38	128.9	63.8	2.388	1.78
193	3	4.5	18.0	8.38	128.6	63.8	2.389	1.78
193	3	4.5	18.0	8.38	128.8	63.7	2.389	1.78
193	3	4.5	18.0	8.38	128.8	63.6	2.389	1.78
193	3	5.5	22.0	7.72	136.7	63.8	2.899	1.62
193	3	5.5	22.0	7.72	136.8	63.7	2.899	1.62
193	3	5.5	22.0	7.72	137.1	63.8	2.898	1.62
193	3	5.5	22.0	7.72	136.8	63.8	2.899	1.62
194	3	1.5	6.0	13.77	101.7	64.2	.814	3.05
194	3	1.5	6.0	13.77	101.7	64.2	.814	3.05
194	3	1.5	6.0	13.77	101.8	64.3	.813	3.05
194	3	1.5	6.0	13.77	102.0	64.4	.813	3.05
194	3	2.0	8.0	10.96	107.3	64.0	1.080	2.39
194	3	2.0	8.0	10.96	106.9	63.6	1.081	2.39
194	3	2.0	8.0	10.96	106.6	63.2	1.081	2.39
194	3	2.0	8.0	10.96	106.3	63.1	1.082	2.39
194	3	2.5	10.0	11.43	112.0	63.6	1.345	2.49
194	3	2.5	10.0	11.43	112.0	63.5	1.345	2.49
194	3	2.5	10.0	11.43	112.0	63.6	1.345	2.49
194	3	2.5	10.0	11.43	112.0	63.5	1.345	2.49
194	3	3.5	14.0	9.72	121.4	63.7	1.867	2.09
194	3	3.5	14.0	9.72	121.8	63.7	1.866	2.08
194	3	3.5	14.0	9.72	121.6	63.7	1.866	2.08
194	3	3.5	14.0	9.72	121.1	63.6	1.868	2.09
194	3	4.5	18.0	8.64	128.9	63.8	2.384	1.84
194	3	4.5	18.0	8.64	128.6	63.8	2.385	1.84
194	3	4.5	18.0	8.64	128.8	63.7	2.385	1.84
194	3	4.5	18.0	8.64	128.8	63.6	2.385	1.84
194	3	5.5	22.0	7.57	136.7	63.8	2.894	1.59
194	3	5.5	22.0	7.57	136.8	63.7	2.894	1.59
194	3	5.5	22.0	7.57	137.1	63.8	2.893	1.59
194	3	5.5	22.0	7.57	136.8	63.8	2.894	1.59
195	3	1.0	4.0	17.19	94.9	64.2	.546	3.88
195	3	1.0	4.0	17.19	94.2	64.1	.546	3.88
195	3	1.0	4.0	17.19	94.3	64.3	.546	3.88
195	3	1.0	4.0	17.19	94.6	64.5	.546	3.88
195	3	1.5	6.0	14.02	101.7	64.2	.814	3.11

RUN NO	NO OF PAR	ETHYL ENE CC/SC	HYDRO GEN CC/SC	CON VER SION	SURF TEMP C	BULK TEMP C	REYNOLDS NUMBER	J FAC
195	3	1.5	6.0	14.02	101.7	64.2	.814	3.11
195	3	1.5	6.0	14.02	101.8	64.3	.813	3.11
195	3	1.5	6.0	14.02	102.0	64.4	.813	3.11
195	3	2.0	8.0	12.29	107.3	64.0	1.080	2.69
195	3	2.0	8.0	12.29	106.9	63.6	1.081	2.69
195	3	2.0	8.0	12.29	106.6	63.2	1.081	2.69
195	3	2.0	8.0	12.29	106.3	63.1	1.082	2.69
195	3	2.5	10.0	11.09	112.0	63.6	1.345	2.41
195	3	2.5	10.0	11.09	112.0	63.5	1.345	2.41
195	3	2.5	10.0	11.09	112.0	63.6	1.345	2.41
195	3	2.5	10.0	11.09	112.0	63.5	1.345	2.41
195	3	3.5	14.0	9.56	121.4	63.7	1.867	2.05
195	3	3.5	14.0	9.56	121.8	63.7	1.866	2.05
195	3	3.5	14.0	9.56	121.6	63.7	1.866	2.05
195	3	3.5	14.0	9.56	121.1	63.6	1.868	2.05
195	3	4.5	18.0	8.44	128.9	63.8	2.384	1.79
195	3	4.5	18.0	8.44	128.6	63.8	2.385	1.79
195	3	4.5	18.0	8.44	128.8	63.7	2.385	1.79
195	3	4.5	18.0	8.44	128.8	63.6	2.385	1.79
195	3	5.5	22.0	7.69	136.7	63.8	2.894	1.62
195	3	5.5	22.0	7.69	136.8	63.7	2.894	1.62
195	3	5.5	22.0	7.69	137.1	63.8	2.893	1.62
195	3	5.5	22.0	7.69	136.8	63.8	2.894	1.62
211	3	1.0	4.0	14.15	54.0	29.8	.595	3.20
211	3	1.0	4.0	14.15	53.5	29.8	.595	3.20
211	3	1.0	4.0	14.15	53.7	29.7	.595	3.20
211	3	1.5	6.0	16.92	62.5	30.2	.884	3.84
211	3	1.5	6.0	16.92	62.8	30.2	.884	3.84
211	3	1.5	6.0	16.92	63.0	30.3	.884	3.84
211	3	2.0	8.0	10.21	67.9	30.2	1.173	2.25
211	3	2.0	8.0	10.21	67.7	30.4	1.173	2.25
211	3	2.0	8.0	10.21	68.0	30.5	1.172	2.25
211	3	2.5	10.0	11.02	73.1	29.2	1.461	2.42
211	3	2.5	10.0	11.02	73.2	29.3	1.460	2.42
211	3	2.5	10.0	11.02	73.3	29.1	1.460	2.42
211	3	3.5	14.0	8.90	80.3	28.8	2.032	1.92
211	3	3.5	14.0	8.90	80.3	28.8	2.032	1.92
211	3	3.5	14.0	8.90	82.1	28.8	2.028	1.92
211	3	4.5	18.0	7.26	89.2	28.6	2.591	1.55
211	3	4.5	18.0	7.26	89.8	28.7	2.589	1.55
211	3	4.5	18.0	7.26	89.8	27.6	2.592	1.55
211	3	5.5	22.0	6.86	97.3	27.7	3.145	1.45
211	3	5.5	22.0	6.86	97.0	27.8	3.146	1.45
211	3	5.5	22.0	6.86	97.7	27.8	3.144	1.45
211	3	5.5	22.0	6.86	97.9	27.8	3.143	1.45
212	3	1.0	4.0	11.92	54.0	29.8	.593	2.67

RUN NO	NO OF PAR	ETHYL ENE CC/SC	HYDRO GEN CC/SC	CON VER SION	SURF TEMP C	BULK TEMP C	REYNOLDS NUMBER	J FAC
212	3	1.0	4.0	11.92	53.5	29.8	.594	2.67
212	3	1.0	4.0	11.92	53.7	29.7	.594	2.67
212	3	1.5	6.0	12.03	62.5	30.2	.883	2.68
212	3	1.5	6.0	12.03	62.8	30.2	.882	2.68
212	3	1.5	6.0	12.03	63.0	30.3	.882	2.68
212	3	2.0	8.0	9.33	67.9	30.2	1.171	2.04
212	3	2.0	8.0	9.33	67.7	30.4	1.171	2.05
212	3	2.0	8.0	9.33	68.0	30.5	1.170	2.04
212	3	2.5	10.0	9.53	73.1	29.2	1.458	2.08
212	3	2.5	10.0	9.53	73.2	29.3	1.458	2.08
212	3	2.5	10.0	9.53	73.3	29.1	1.458	2.08
212	3	3.5	14.0	9.33	80.3	28.8	2.028	2.02
212	3	3.5	14.0	9.33	80.3	28.8	2.028	2.02
212	3	3.5	14.0	9.33	82.1	28.8	2.025	2.02
212	3	4.5	18.0	7.22	89.2	28.6	2.586	1.54
212	3	4.5	18.0	7.22	89.8	28.7	2.584	1.54
212	3	4.5	18.0	7.22	89.8	27.6	2.587	1.54
212	3	5.5	22.0	6.66	97.3	27.7	3.139	1.41
212	3	5.5	22.0	6.66	96.9	27.8	3.140	1.41
212	3	5.5	22.0	6.66	97.7	27.8	3.138	1.41
212	3	5.5	22.0	6.66	97.9	27.8	3.137	1.41
213	3	1.0	4.0	12.23	54.0	29.8	.591	2.74
213	3	1.0	4.0	12.23	53.5	29.8	.592	2.74
213	3	1.0	4.0	12.23	53.7	29.7	.591	2.74
213	3	1.5	6.0	11.15	62.5	30.2	.879	2.47
213	3	1.5	6.0	11.15	62.8	30.2	.879	2.47
213	3	1.5	6.0	11.15	63.0	30.3	.879	2.47
213	3	2.0	8.0	13.29	67.9	30.2	1.167	2.96
213	3	2.0	8.0	13.29	67.7	30.4	1.167	2.96
213	3	2.0	8.0	13.29	68.0	30.5	1.166	2.96
213	3	2.5	10.0	9.76	73.1	29.2	1.452	2.13
213	3	2.5	10.0	9.76	73.2	29.3	1.452	2.13
213	3	2.5	10.0	9.76	73.3	29.1	1.452	2.13
213	3	3.5	14.0	8.15	80.3	28.8	2.021	1.76
213	3	3.5	14.0	8.15	80.3	28.8	2.020	1.76
213	3	3.5	14.0	8.15	82.1	28.8	2.017	1.75
213	3	4.5	18.0	7.52	89.2	28.6	2.577	1.60
213	3	4.5	18.0	7.52	89.8	28.7	2.575	1.60
213	3	4.5	18.0	7.52	89.8	27.6	2.578	1.60
213	3	5.5	22.0	7.35	97.3	27.7	3.128	1.56
213	3	5.5	22.0	7.35	97.0	27.8	3.129	1.56
213	3	5.5	22.0	7.35	97.7	27.8	3.126	1.56
213	3	5.5	22.0	7.35	97.9	27.8	3.126	1.56
214	3	1.0	4.0	11.95	54.0	29.8	.591	2.68
214	3	1.0	4.0	11.95	53.5	29.8	.591	2.68
214	3	1.0	4.0	11.95	53.7	29.7	.591	2.68

RUN NO	NO OF PAR	ETHYL ENE CC/SC	HYDRO GEN CC/SC	CON VER SION	SURF TEMP C	BULK TEMP C	REYNOLDS NUMBER	J FAC
214	3	1.5	6.0	10.76	62.5	30.2	.878	2.38
214	3	1.5	6.0	10.76	62.8	30.2	.878	2.38
214	3	1.5	6.0	10.76	63.0	30.3	.878	2.38
214	3	2.0	8.0	10.28	67.9	30.2	1.165	2.26
214	3	2.0	8.0	10.28	67.7	30.4	1.165	2.26
214	3	2.0	8.0	10.28	68.0	30.5	1.165	2.26
214	3	2.5	10.0	9.49	73.1	29.2	1.451	2.07
214	3	2.5	10.0	9.49	73.2	29.3	1.451	2.07
214	3	2.5	10.0	9.49	73.3	29.1	1.451	2.07
214	3	3.5	14.0	8.03	80.3	28.8	2.019	1.73
214	3	3.5	14.0	8.03	80.3	28.8	2.019	1.73
214	3	3.5	14.0	8.03	82.1	28.8	2.015	1.73
214	3	4.5	18.0	7.88	89.2	28.6	2.574	1.68
214	3	4.5	18.0	7.88	89.8	28.7	2.572	1.68
214	3	4.5	18.0	7.88	89.8	27.6	2.576	1.68
214	3	5.5	22.0	7.61	97.3	27.7	3.125	1.61
214	3	5.5	22.0	7.61	97.0	27.8	3.126	1.61
214	3	5.5	22.0	7.61	97.7	27.8	3.124	1.61
214	3	5.5	22.0	7.61	97.9	27.8	3.123	1.61
215	3	5.5	22.0	6.47	97.3	27.7	3.122	1.36
215	3	5.5	22.0	6.47	96.9	27.8	3.123	1.37
215	3	5.5	22.0	6.47	97.7	27.8	3.121	1.36
215	3	5.5	22.0	6.47	97.9	27.8	3.120	1.36
216	3	1.0	4.0	12.56	54.0	29.8	.590	2.82
216	3	1.0	4.0	12.56	53.5	29.8	.590	2.82
216	3	1.0	4.0	12.56	53.7	29.7	.590	2.82
216	3	1.5	6.0	12.71	62.5	30.2	.877	2.84
216	3	1.5	6.0	12.71	62.8	30.2	.877	2.83
216	3	1.5	6.0	12.71	63.0	30.3	.876	2.83
216	3	2.0	8.0	10.78	67.9	30.2	1.163	2.38
216	3	2.0	8.0	10.78	67.7	30.4	1.163	2.38
216	3	2.0	8.0	10.78	68.0	30.5	1.163	2.38
216	3	2.5	10.0	9.95	73.1	29.2	1.449	2.17
216	3	2.5	10.0	9.95	73.2	29.3	1.448	2.17
216	3	2.5	10.0	9.95	73.3	29.1	1.448	2.17
216	3	3.5	14.0	8.60	80.3	28.8	2.015	1.86
216	3	3.5	14.0	8.60	80.3	28.8	2.015	1.86
216	3	3.5	14.0	8.60	82.1	28.8	2.012	1.85
216	3	4.5	18.0	7.37	89.2	28.6	2.570	1.57
216	3	4.5	18.0	7.37	89.8	28.7	2.568	1.57
216	3	4.5	18.0	7.37	89.8	27.6	2.571	1.57
216	3	5.5	22.0	6.99	97.3	27.7	3.119	1.48
216	3	5.5	22.0	6.99	97.0	27.8	3.120	1.48
216	3	5.5	22.0	6.99	97.7	27.8	3.118	1.48
216	3	5.5	22.0	6.99	97.9	27.8	3.118	1.48

APPENDIX E

INDICATION THAT THE REACTION IS FILM-DIFFUSION CONTROLLED

The method most widely used to determine whether a reactor is operating in the diffusion controlled or reaction rate controlled regime is outlined as follows (11):

(1) Measure the conversion, x, at some value of W/F, where W is the weight of catalyst and F is the reactant flow rate.

(2) Increase W and F in the same proportions so as to keep the ratio W/F constant and measure the conversion again.

(3) Repeat this procedure for several values of W/F.

(4) Plot x versus W/F for each value of W/F.

(5) If the lines coincide, the reaction is reaction rate controlled. If the lines do not coincide, the reaction is diffusion controlled.

Shown in Figure 8 on page 74 is a plot of this nature. Since all of the catalyst particles were nearly the same size, the ratio N/F, where N is the number of catalyst particles and F is the ethylene flow rate, was plotted instead of W/F. Runs 131 and 181 were chosen for this plot. Run 131 was made with nine catalyst particles in the bed at a bulk gas temperature of 97°C and run 181 was made with three catalyst particles in the bed at a bulk gas temperature of 94°C.

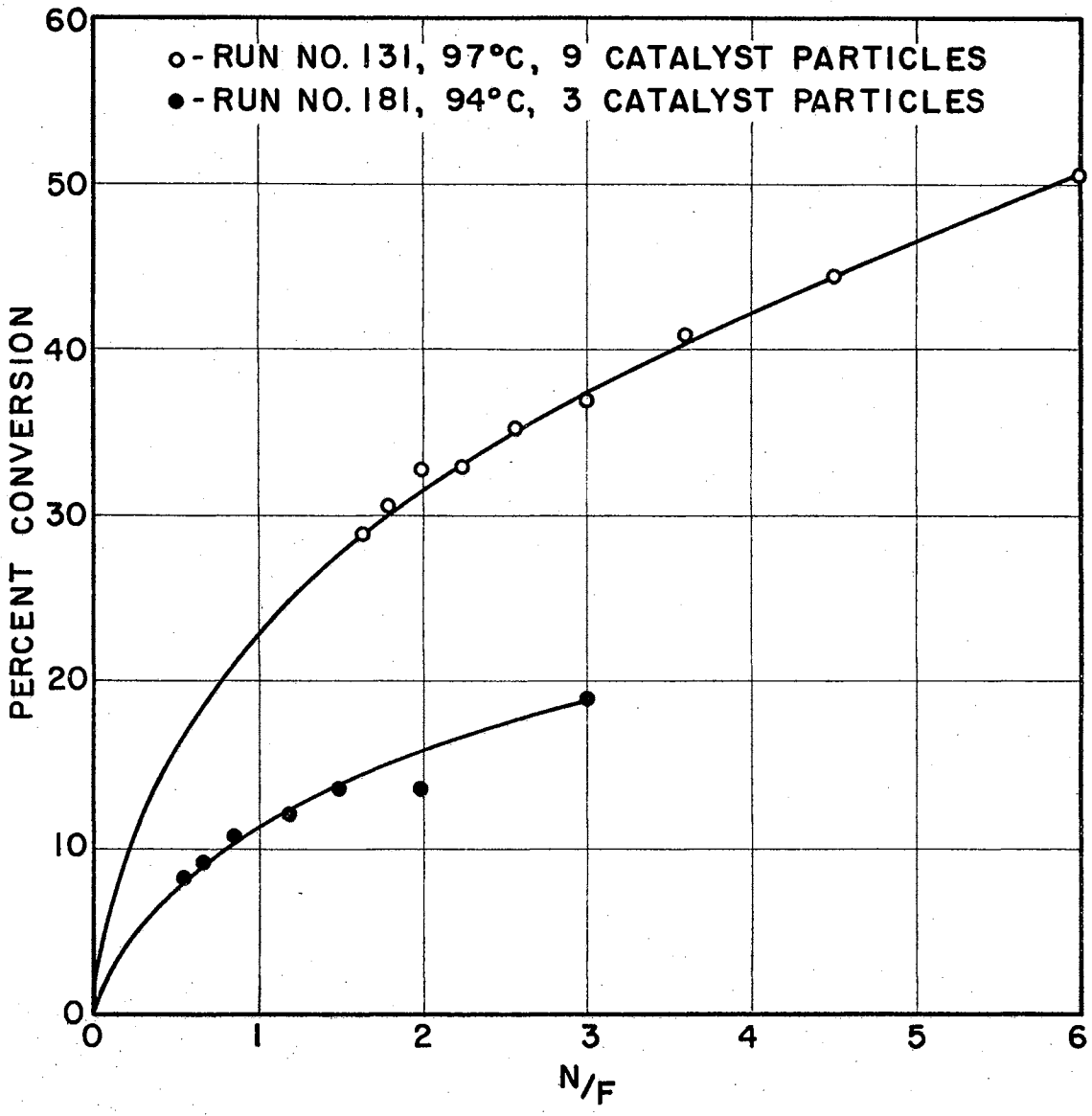


Figure 8. Dependence of Conversion upon N/F Ratio; Graphical Indication That the Reaction Is Diffusion-Controlled

VITA

Berry Crain, Jr.

Candidate for the Degree of

Master of Science

Thesis: MASS TRANSFER IN A PACKED BED REACTOR AT LOW REYNOLDS NUMBERS: THE HYDROGENATION OF ETHYLENE TO ETHANE ON NICKEL CYLINDERS

Major Field: Chemical Engineering

Biographical:

Personal Data: Born in Memphis, Tennessee, August 11, 1941, the son of Berry and Inez C. Crain. Married to Diane Rhodes Hoke, Starkville, Mississippi. Son: Gregory Hoke.

Education: Attended grade school in Brandon, Mississippi; graduated from Brandon High School, Brandon, in 1959; received the Bachelor of Science degree from Mississippi State University in August, 1963; completed the requirements for the Master of Science degree in May, 1965.