APPENDIX B

SITE CONDITIONS

Date 8/8/75
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Job No. 5435-0003

Job Name Fischer-Tropsch Conceptual Com'l Plant   Project Manager ________

Motor Fuel and SNG from Coal (ERDA)

1.0 GENERAL AND METEOROLOGICAL

1.01 Location Eastern Region, U.S. Interior Coal Province

1.02 Elevation 490 ft

1.03 Climatic Conditions % Relative Humidity High: 80 Low: 50

a. Maximum temperature 103 °F; Design for 90 °F

b. Minimum temperature -15 °F; Design for -15 °F

c. Design wet bulb temperature 78 °F

d. Rainfall 38 in. per yr. (average): 0.75 in. per hr. (design)

e. Average wind velocity 12 miles per hour

f. Maximum wind velocity 50 miles per hour (gusts)

g. Direction of wind NW 1Q; NW-SSW 2Q; S 3Q; S-NW

h. Average annual snow fall 20 inches per year

j. Design for 25 PSF snow pack (omit if roof load known)

k. Frost line — Design for 24 inches depth

l. Lightning storms — Number per year 50

m. Dust Storms — Are special provisions required? NO-Hail & Tornadoes occur March thru June

2.0 STRUCTURAL DATA

2.01 Vertical Live Loads

a. Roofs, tank tops, etc., on horizontal projected area

Area in Sq. Ft.:	0-200	200-600	Over 600
Rise less than 4 in./ft.	25	25	25 psf
Rise 4 in./ft. and steeper	per UBC	√	√ psf

b. Platform, stairs and walks

	Loading
1. Pedestrian traffic only	75 psf
2. Work area – uniform loading	50 psf
3. Work area – concentrated loading	320 psf

c. Floors on ground

	Uniform Load	Concentrated Load
1. Control houses	100 psf*	1,000 on 2 1/2" sg.**
2. Paved areas	100 psf*	15,000 wheel load
3. Other buildings	100 psf	
a. Maintenance Bldg	250 psf	
b. Lab & Admin Bldg	75 psf	
c. Stores/Whse	100 psf	15,000 wheel load

d. Vessels and piping

1. See detailed sheet for weight of normal operating liquid contents.

2.02 Empty Condition

Weight of equipment in place and empty, with removable internal parts all installed and with dead load attachments such as platforms and operating lines in place, plus wind or earthquake.

2.03 Test Condition

Empty weight plus weight of test water, without wind or earthquake.

2.04 Operating Condition

Empty weight plus weight of liquid at maximum level, plus wind or earthquake or expansion forces.

*100 Recommended
**1000 Recommended

2.05 Lateral Loads (Wind)

a. Wind on vertical flat projected areas

0 to 30 feet above ground	15	psf
30 to 50 feet above ground	20	psf
50 to 100 feet above ground	25	psf
100 to 500 feet above ground	30	psf

b. For circular equipment the wind pressure shall be assumed to act on 0.6 of projected area.

c. For computing wind pressure on exposed open frame structures, use 130 percent of projected areas of all members.

2.06 Lateral Load (Earthquake)

Uniform Building Code Zone #2

Note: Wind and earthquake forces are not additive.

2.07 Allowable Stresses may be increased 1/3 for lateral loadings, and 1/5 during hydrostatic test.

2.08 Stability Ratio

a. Minimum allowable stability ratio = $\frac{\text{Stabilizing Moment}}{\text{Overturning Moment}} = 1.5$

b. Soil bearing foundations to have positive soil pressure over whole footing, except for erection load conditions (Provided that toe pressure does not exceed allowable soil bearing pressure).

3.0 FOUNDATIONS AND SOIL DATA

3.01 Soil Data

a. Type of Soil Sand — Rocky

b. Subsoil strata a factor? NO

c. Elevations of water table Varies

d. Is piling required? NO

e. Special soil analysis reference To be determined

3.01 Soil Data (Continued)

f. Excavation remarks ________

3.02 Foundations

a. Allowable Bearing Loads

	Type of Soil	Depth	Vertical Load	Lateral Load
1.	Sand & Rocky	3 ft.	3,000 psf	– psf
2.	–	– ft.	– psf	– psf

b. Ultimate Compressive Strength after 28 days

1. Reinforced concrete 3,000 psf

c. Minimum Coverage of Reinforced Steel

1. Formed sections 2 in. (except 1 1/2 in. for #5 and smaller bars)
2. Unformed sections 3 in.
3. Water contact 3 in.

d. Minimum Depth of Foundations

1. Exterior walls and/or piers 3 ft.
2. Interior building footings 3 ft.
3. Frost line 3 ft.
4. Ground water depth 4 – 20 ft.
5. Are termites and fungi a factor? Yes

e. Elevations

1. Base elevation (Refinery Datum) 100.00 ft.
2. Existing ground elevation 460 – 490 ft.
3. Finished grade To be determined ft.
4. High point of paving To be determined ft.

4.0 UTILITIES

4.01 Air

a. Instrument air at 60 psi and maximum dew point -20 °F at 100 psi

b. Utility air at 90 psi

c. Starting air for compressors at Atmos psi

4.02 Cooling Water

a. Type Tower

b. Maximum cold water temperature – °F

c. Design cold water temperature 80 °F

d. Maximum hot water temperature 120 °F

e. Design hot water temperature 120 °F

f. Design water supply pressure at grade 50 PSIG

g. Design water return pressure at grade 35 PSIG

4.03 Cooling Tower

a. Water inlet temperature 100 °F

b. Water outlet temperature 86 °F

c. Design wet bulb 78 °F

d. Type of tower Mechanical Draft Cross Flow

e. Structural design-lateral load: See Section 2.0

4.04 Steam and Condensate

a. High pressure steam at 1145 psi and 300 °F superheat

b. Low pressure steam at 50 psi and – °F superheat

c. Intermediate pressure steam at 475 psi and ____ °F superheat

d. Condensate system at 50 psi

4.05 Boiler Feedwater

a. Supply pressure at plot limit 60 psi

b. Supply temperature at plot limit 60 °F

4.06 Fuel Gas

	Natural Gas	Refinery Gas
a. Pressure at plot limit	X psi	60 psig
b. Heating value at 1 atm	X Btu/cu. ft	X Btu/cu. ft.

c. Composition ______

4.07 Air Coolers 30 °F Approach 120 °F min

4.08 Liquid Fuel

a. Type ______

b. SP Gravity ______

c. Viscosity (poises at 210 °F) ______

d. Heating value ______ Btu/lb.

e. Supply pressure at plot limit ______ psi

f. Return pressure at plot limit ______ psi

g. Temperature at plot limit ______ °F

4.09 Water Systems

	Supply Pressure	Supply Temperature	Required Treatment
a. Drinking	50-70 psi	Ambient °F	Settled, Demineralized, and Chlorinated
b. Sanitary	50-70 psi	Ambient °F	Settled, Demineralized, and Chlorinated
c. Fire System	90 psi	Ambient °F	Raw River Water

4.10 Sewers

a. Types

1. Sanitary Yes
2. Oily Water Yes
3. Surface Runoff Ditches
4. Chemical Yes
5. Combine 2 and 3? No

b. Materials and Installations

Location	Sewer Systems: Sanitary	Oily Water	Runoff	Other
1. Inside Buildings	CI	CI	–	–
2. Under concrete	CI	CI	CI	–
3. Under unpaved areas	VC to 12" RC > 12"	VC to 12" RC > 12"	Ditch	–
4. Design Velocity*	3-5 ft/sec	3-5 ft/sec	Under pavement 3-5 ft/sec	–
5. Slope (%)	As Below**	2%	1%	–
6. Minimum Coverage	3 ft	3 ft	3 ft	–
7. Manholes Precast Concrete	At junctions and changes of direction Sealed @ 300' min distance			–
8. Manhole Covers CI	Plain	Bolted & Gasketed	Bolted & Gasketed	–
9. Junction Boxes	None	Sealed	Sealed	–

*3-5 recommended.
**Minimum 2% to septic tank, 1% beyond.

5.0 ELECTRICAL EQUIPMENT

5.01 Power Supply and Characteristics

a. Source In Plant Generation – Emergency Firm Power from local Utility Company

b. Routing Overhead, Trays

c. Service

	Service	Volts	Phase	Cycle
1.	Main supply	138K	3	60
2.	Primary distribution	138K	3	60
3.	Secondary distribution	2300/480	3	60
4.	Lighting	480/240/120	3	60
5.	Emergency heating	–	–	–
6.	Electrical Instrumentation	24	–	DC

5.02 Switchgear and Design Details

a. Refer to "Electrical Design Criteria Project No. – "

03 Material Classification – See Drawing –

a.	Hazardous areas	Class 1, Group D, Division 1
b.	Semi-hazardous	Class 1, Group D, Division 2
c.	Non-hazardous	NEMA

Motors

a.	Size 150 hp and up	2200 volts	3 phase
.	Size 3/4 hp to 125 hp	480 volts	3 phase
	Size 1/2 hp and smaller	120 volts	3 phase

5.05 Metering

a. Main Supply By plant powerhouse

b. Others To be determined

6.0 INSTRUMENTS

6.01 Accounting Meters Required

	Yes		No
a. Plant feed streams	X		
b. Plant product streams	X		
c. ____________ steam system	X		
d. ____________ steam system	X		
e. Fresh water	X		
f. Sanitary water			X
g. Cooling water	X	As process requires	
h. Air			X
i. Fuel gas	X		
j. Fuel oil	X		

k. Others Chlorine, Sulfuric Acid, NaOH, KOH (liquid)

6.02 Panelboard

a. Type Local Panels and Main Control Center

b. Instruments Pneumatic and Electronic; Computer Controlled

c. Arrangement of instruments –

d. Chart drives Electrical

6.03 Emergency supply of instrument air Yes

6.04 Instrument air cooler and dryer Yes

6.05 Master instrument air filters — Yes

7.0 PROCESS DATA

7.01 Product to Storage Temperatures

a.	LPG	100 °F		Gas Oil	120 °F
b.	Pen-hex	- °F		Diesel Oil	- °F
c.	Gasoline	- °F		Fuel Oil	180 °F
d.	Light naphtha	100 °F		Asphalt	°F
e.	Heavy naphtha	100 °F		Two	°F
f.	Kerosene	°F		Pitch	°F
g.	Others			Others	
	Liquid Sulfur:	250 + °F		Solid Sulfur:	Ambient

7.02 Equipment Data

		Normal Contingency	Process Control Contingency	
a.	Pumps			
	Feed	%	10 %*	
	Reflux, Furnace, Recirc	%	20 %	
	Product	%	10 %	
b.	Compressors	%	10 %	
c.	Heat exchangers	%	0 %	
d.	Furnaces	%	10 %	IMM Btu Minimum
e.	Cooling tower	%	10 %	
f.	Others	%	%	
		%	%	

*Contingency for large pumps and compressors to be reviewed on a case by case basis (500 HP and over)

7.03 Codes — latest editions

a. API-ASME unfired Pressure Vessel
   API 650 — Storage Tanks
   ASME, Section VIII, Div. 2

b. ASA Piping Code
   USAS B 31.3 — 1966 — Piping
   USAS B 16.5 — Flanges and Fittings
   USAS B 31.1 — Power Piping

c. ASME Code Power Boilers — Section I

d. National Electric Code NEMA

e. Uniform Building Code (by International Conference of Bldg. Officials.)

f. National Plumbing Code IBC

g. Petroleum Safety Orders Apply

h. Exceptions to codes None

8.0 MISCELLANEOUS

8.01 Safety

a. Maximum temperature for safety to personnel 140 °F

b. Hazardous chemicals Chlorine, Caustic, Sulfuric Acid

8.02 Winterization

a. Design considerations Yes, -5°F for water, steam condensate and various process lines and instrumentation

b. Degree required As dictated by process requirements

8.03 Noise abatement a factor Yes, all fans, compressors, generators and pipelines

8.04 Air pollution requirements Yes, per Federal and State of Illinois Requirements

8.05 Water pollution requirements Yes, per above

8.06 Aircraft warning regulations Yes, per above

8.07 Shipping problems None – Truck and Railway both available

APPENDIX C

ANALYSIS AND DESIGN

EXTENDED SURFACE CATALYTIC REACTOR/HEAT EXCHANGER

D. L. Burford and J. P. Callinan*

The Parsons Fischer-Tropsch conceptual commercial design includes unique catalytic reactors for the Fischer-Tropsch synthesis, shift conversion and methanation units.[1,2,3,4,5] These reactors have flame sprayed catalysts (FSC) applied to all or a portion of the outside surface of a fin tube (extended surface) heat exchanger with coolant inside the tubes. This configuration results in efficient transfer of heats of reaction energy to high level energy streams such as 1200 psig steam.

To effectively complete the Fischer-Tropsch design, it was necessary to develop procedures for analysis of the heat and reaction factors and design of this unique reactor type; these procedures did not exist in the detail required. The analysis/design techniques were successfully developed and the results are summarized in the following pages of this APPENDIX.

The Analysis of Fin with Catalytic Reaction on the Surface

Typical finned tubes which could be employed in finned catalytic heat exchangers are illustrated in Figure 1. The catalyst would be deposited (e.g., flame sprayed[3]) on all or part of the finned side of the tube. Variations (e.g., the entire finned side of the tube coated with the catalyst, alternate fins coated or fins coated on one side only) would permit designing the heat exchanger to achieve optimal temperatures. The reactant gas flows over the finned surface while the coolant (possibly a phase change substance) would flow through the inside of the tubes.

The work which follows is a thermal analysis of fins on whose surface a chemical reaction is occurring and a thermal analysis of simple heat exchangers employing finned, catalytic surfaces.

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A fin of arbitrary geometry is shown in Figure 2. In analyzing this fin, the usual fin assumptions [6, pp. 85 and 86] are made. In addition, it is assumed that an exothermic chemical reaction is occurring on the surface of the fin, releasing energy at the surface.[3] A heat balance on the surface area element $P(x)dx$ yields: the heat convected from the surface plus the heat conducted from the surface equals the heat released at the surface due to the chemical reaction. The heat convected from the surface is:

$$dq_c = h(T - T_\infty)\ P(x)dx \tag{1}$$

Where T is the surface temperature,

T_∞ is the fluid temperature,

$P(x)$ is the fin perimeter, and

h is the convective heat transfer coefficient (assumed constant and includes the effect of mass transfer on heat transfer).

The heat conducted from the surface equals the net heat conducted out of the volume element $A(x)dx$,

$$dq_k = -k\ \frac{d}{dx}\left[A(x)\frac{dT}{dx}\right]\ dx \tag{2}$$

Where k is the thermal conductivity and
$A(x)$ is the cross sectional area of the fin.

The energy released by the chemical reaction occurring at the surface is

$$dq_r = \dot{Q}\ P(x)dx \tag{3}$$

Where $\dot{Q}$ is the energy release rate per unit catalytic surface area and is assumed constant (for endothermic reactions, $\dot{Q}$ is a negative number).

Combining equations (1), (2) and (3) to form a heat balance at the surface yields

$$h(T - T_\infty)p(x)dx\ -\ K\ \frac{d}{dx}\left[A(x)\frac{dt}{dx}\right]dx = \dot{Q}P(x)dx \tag{4}$$

This can be rearranged as follows

$$A(x)\frac{d^2T}{dx^2} + \frac{dT}{dx}\frac{dA(x)}{dx} - \frac{hP(x)}{K}\left[T - (T_\infty + \frac{\dot{Q}}{h})\right] = 0 \tag{5}$$

Defining the following dimensionless variables,

$$\xi = x/L \tag{6}$$

$$\theta = [T - (T_\infty + \dot{Q}/h)]/[T_L - (T_\infty + \dot{Q}/h)] \tag{7}$$

$$f_1(\xi) = A(L\xi)/L^2 \tag{8}$$

$$f_2(\xi) = P(L\xi)/L \tag{9}$$

$$B = h\ L/K \tag{10}$$

Equation (5) becomes

$$f_1(\xi)\ \frac{d^2\theta}{d\xi^2} + \frac{d\theta}{d\xi}\ \frac{df_1(\xi)}{d\xi} - f_2(\xi)B\theta = 0 \tag{11}$$

Where L = the fin length and

T_L = the fin base temperature

Typical boundary conditions are:

at $\xi = 0$, (a) $\frac{d\theta}{d\xi} = 0$ (adiabatic tip) (12-a)

or (b) $\frac{d\theta}{d\xi} = B\theta$ (convective tip) (12-b)

and at $\xi = 1$, $\theta = 1$ (base temperature is known) (13)

Equation (11) with its boundary conditions, equations (12) and (13), is identical to the heat conduction equation for a conventional fin of arbitrary geometry (Ref. 6, Chapter 2). It follows that published solutions to this equation for conventional fins of various specific geometries are also applicable to the catalytic fins of identical geometry discussed here. In applying these existing solutions to catalytic fins, one simply replaces the fluid temperature, T_∞, with an effective fluid temperature, T_∞^*, defined as

$$T_\infty^* = T_\infty + \dot{Q}/h \tag{14}$$

In general, the heat transfer through the base of the fin is given by

$$q_f = -hS[T_L - T_\infty^*]\,\eta_f \tag{15}$$

and the heat transfer to the fluid is given by

$$q_\infty = \dot{Q}S - q_f \tag{16}$$

Where S is the surface area of the fin.

Fin efficiencies, η_f, for specific fin geometries appear in the heat transfer literature (e.g., Ref. 4, pp. 97, 110, 123 and 135 through 162).

As an example, consider the longitudinal fin of constant profile (Figure 1-a) with an adiabatic tip. From the well-known solution for the conventional fin of this geometry, the fin temperature distribution is

$$\theta = \frac{\cosh[mL(1-\xi)]}{\cosh mL} \tag{17}$$

Where $m^2 = hP/kA$ (18)

P = perimeter (constant)

A = cross sectional area (constant)

And, the rate of heat transfer through the base of the fin is given by equation (15) where

$$\eta_f = \frac{\tanh(mL)}{mL} \tag{19}$$

Analysis of Heat Exchangers Employing Catalytic Fins

A section of a generalized heat exchanger tube is shown in Figure 3. In this heat exchanger some of the finned area, S_{fc}, has a catalytic coating and the remainder, S_{fu}, doesn't. Also, a portion of the outside (unfinned) surface area of the tube, S_{bc}, is coated and the remainder, S_{bu}, is not. The heat flow to the coolant in the tube can be divided into two parallel paths, that coming from the catalytic portion of the tube outer surface, q_{ic}, and that coming from the reactant gas through the uncoated surface, q_{iu}.

By making a heat balance on a differential element of the surface where the catalytic reaction is occurring (similar to what was done in the previous section) it can be shown that

$$dq_{ic} = U_c(T_\infty + \frac{\dot{Q}}{h} - T_i)\ ds_o \tag{20}$$

where

$$\frac{1}{U_c} = \frac{S_o}{h_i S_{ic}} + r_{fi}\frac{S_o}{S_{ic}} + \frac{tS_o}{kS_{mc}} + \frac{S_o}{h(A_{bc} + \eta_f A_{fc})} \tag{21}$$

S_o = total outside surface area

S_{ic} = inside surface area adjacent to catalytic fins

r_{fi} = fouling resistance on inside of tube

S_{mc} = mean tube wall surface area adjacent to catalytic fins

S_{bc} = catalytically coated tube outside surface area between fins

S_{fc} = catalytically coated fin surface area

S_c = $S_{bc} + S_{fc}$ = total catalytically coated area

t = tube thickness

k = tube thermal conductivity

h_i = convective heat transfer coefficient on inside of tube

h = convective heat transfer coefficient on outside of tube

s_o = the outside surface area variable, varying from 0 to S_o from the beginning to the end of the exchanger

For the uncoated portion of the tube,

$$dq_{iu} = U_u \; (T_\infty - T_i) ds_o \tag{22}$$

where

$$\frac{1}{U_u} = \frac{S_o}{h_i S_{iu}} + r_{fi} \frac{S_o}{S_{iu}} + \frac{tS_o}{kS_{mu}} + \frac{S_o}{\bar{h}(S_{bu} + \eta_f S_{fu})} \tag{23}$$

where the nomenclature is similar to that in equation (21) except it is referred to the uncoated portion of the tube.

The total heat transfer to the coolant is, from eqs. (20) and (22),

$$dq_i = dq_{ic} + dq_{iu}$$

$$= U(T_\infty - T_i) \; ds_o + \frac{U_c}{h} \; \dot{Q} ds_o \tag{24}$$

where $U = U_u + U_c$

Since the only heat source is the catalytic reaction, the heat transfer to the reactant gas is

$$dq_\infty = \dot{Q} \frac{S_c}{S_o} \; ds_o - dq_i$$

$$= \dot{Q} \; \frac{S_c}{S_o} - \frac{U_c}{h} \quad ds_o - U \; (T_\infty - T_i) ds_o \tag{25}$$

For this differential element of the heat exchanger the coolant temperature, T_i, increases by an amount*

$$dT_i = dq_i / C_i \tag{26}$$

where
$$C_i = \dot{m}_i C_{pi} \tag{27}$$

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*Here we are assuming a parallel flow heat exchanger in which the temperatures of both fluids are assumed to increase.

and the temperature of the reactant gas, T , increases by an amount*

$$dT_\infty = dg_\infty / C_\infty \tag{28}$$

where
$$C_\infty = \dot{m}_\infty C_{pi} \tag{29}$$

Combining eqs. (26) and (28),

$$dT_\infty - dT_i = dq_\infty / C_\infty - dq_i / C_i \tag{30}$$

Eliminating dq_∞ and dq_i with equations (24) and (25),

$$dT_\infty - dT_i = \left[\dot{Q} \ \frac{S_c}{S_o} \frac{1}{C_\infty} - \left(\frac{1}{C_\infty} + \frac{1}{C_i} \right) \frac{U_c}{h} \right] ds_o$$

$$- \left(\frac{1}{C_\infty} + \frac{1}{C_i} \right) U \ (T_\infty - T_i) ds_o \tag{31}$$

Defining the following dimensionless variables

$$\Theta = \frac{T_\infty - T_i}{T_{\infty 1} - T_{i1}} \tag{32}$$

Where the subscript 1 refers to the point where $s_o = 0$ (inlet conditions for a parallel flow heat exchanger),

$$X = s_o / S_o \tag{33}$$

$$\beta = \frac{\dot{Q} S_o}{C_\infty (T_{\infty 1} - T_{i1})} \tag{34}$$

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*Here we are assuming a parallel flow heat exchanger in which the temperatures of both fluids are assumed to increase.

$$\delta = \left[\epsilon - (1 + \gamma)\frac{U_c}{h}\right] \tag{35}$$

$$\gamma = C_\infty / C_i$$

$$\epsilon = S_c / S_o \tag{36}$$

and

$$\alpha = (1 + \gamma)\frac{US_o}{C_\infty} \tag{37}$$

Equation (31) becomes

$$d\Theta = \beta\delta\, dX - \alpha\,\Theta\, dX \tag{38}$$

Rearranging eq. (31)

$$\frac{d\Theta}{dX} + \alpha\,\Theta = \beta\delta \tag{39}$$

where the boundary condition is at $X = 0 \quad \Theta = 1$. Solving eq. (39) and eliminating the constant of integration with boundary conditions, the relationship for the temperature difference in the heat exchanger is

$$\Theta = \left(1 - \frac{\beta\delta}{\alpha}\right)e^{-\alpha X} + \frac{\beta\delta}{\alpha} \tag{40}$$

For the entire heat exchanger (i.e., at $X = 1$),

$$\Theta_2 = \left(1 - \frac{\beta}{\alpha}\right)e^{-\alpha} + \frac{\beta\delta}{\alpha} \tag{41}$$

Defining

$$\Theta_i = \frac{T_i - T_{i1}}{T_{\infty 1} - T_{i1}} \tag{42}$$

and

$$\Theta_\infty = \frac{T_\infty - T_{\infty 1}}{T_{\infty 1} - T_{i1}} \tag{43}$$

We note that

$$\theta_\infty - \theta_i = \theta - 1 \tag{44}$$

and further, that

$$\dot{Q}S_c\chi = C_\infty(T_\infty - T_{\infty 1}) + C_i(T_i - T_{i1})$$

or,

$$\epsilon\beta\chi = \theta_\infty + \theta_i/\gamma \tag{45}$$

Combining eqs. (40), (44) and (45) we obtain expressions for the dimensionless temperature of each fluid. For the reactant gas

$$\theta_\infty = \left(\frac{1}{1+\gamma}\right)\left[\epsilon\gamma\beta\chi + \left(\frac{\beta\delta}{\alpha} - 1\right)\left(1 - e^{-\alpha\chi}\right)\right] \tag{46}$$

and for the coolant

$$\theta_i = \left(\frac{\gamma}{\gamma+1}\right)\left[\epsilon\beta\chi - \left(\frac{\beta\delta}{\alpha} - 1\right)\left(1 - \epsilon^{-\alpha\chi}\right)\right] \tag{47}$$

In the design of a catalytic heat exchanger the objective is to produce a specified yield of a particular product of the reaction. The chemical kinetics would specify the reactant gas flow rate, the total surface area of catalyst required and the allowable range of synthesis gas temperature, T_∞. Equations (41), (46) and (47) can then be used to size a heat exchanger which will accomplish these objectives. These same equations apply equally well to the counterflow case and to the case when the coolant undergoes a phase change. For the counterflow case γ must be defined as follows,

$$\gamma = -\frac{C_\infty}{C_i} \tag{48}$$

and the coolant enters the heat exchanger at T_{i2}. For the case in which the coolant undergoes a phase change (i.e., T_i is constant),

$$\gamma = 0 \tag{49}$$

and eq. (47) has no meaning.

The expression for the temperature difference between the reactant gas and the coolant, eq. (40), consists of two terms, an exponential decay term and a constant. As the reactant gas flows through the heat exchanger its temperature changes rapidly at first. As αX gets very large compared to one, T_∞ remains at a fixed increment greater than the coolant temperature. This can be seen by evaluating eq. (40) for $\alpha X >> 1$,

$$\theta = \frac{\beta \delta}{\alpha} \tag{50}$$

and using eqs. (32), (34), (35) and (36) to express it in a dimensional form.

$$T_\infty = T_i + \frac{\dot{Q}}{U}\left[\frac{S_c}{S_o}\left(\frac{1}{1+\gamma}\right) - \frac{U_c}{h}\right] \tag{51}$$

In cases involving highly exothermic reactions, $\alpha >> 10$ and, therefore, $\alpha X >> 1$ occurs for small values of X. Equation (51) states that, under this condition, the reactant gas temperature will remain a constant increment above the coolant temperature. If the coolant temperature increases as X increases (parallel flow case) then the reactant gas temperature will also increase. If the coolant temperature remains constant (phase change case) the reactant gas temperature will also remain constant. Equation (51) shows quantitatively the effect of design parameters on T_∞. For specified values of Q and S_c, the value of T_∞ can be reduced by increasing U, by increasing S_o, by increasing U_c or by decreasing h. It should be noted that these parameters are interrelated.

Example

The following example illustrates the application of the analytical techniques developed above and also illustrates quantitatively the nature of the temperature variations in these heat exchangers.

It is desired to cause 50,000 lb/hr of a reactant gas to undergo a specific shift reaction. 50,000 sq. ft. of catalyst surface are required. The gas enters the heat exchanger at 560°F and it is desirable to control the gas temperature in a range between 590 and 620°F in order to accomplish the desired reaction. A heat exchanger utilizing spiral fins (Fig. 1-b) is selected. It is arbitrarily decided to have $S_c/S_o = 0.5$. The following data are applicable to the particular heat exchanger geometry selected.

$S_c = 50,000$ sq. ft. $\quad S_o = 100,000$ sq. ft.

$S_o/S_i = 10.2 \quad S_o/S_{iu} = S_o/S_{ic} = 20.4$

$S_o/S_{mu} = S_o/S_{mc} = 19.2$

$S_{bu}/S_o = S_{bc}/S_o = 0.042$

$S_{fu}/S_o = S_{fc}/S_o = 0.458$

$\dot{m}_\infty = 50,000$ lb/hr $\quad C_{p_\infty} = 0.6$ Btu/lb°F

$\eta_f = 0.3$, $k = 23$ Btu/hr ft °F

$h = 120$ Btu/hr sq ft °F

$h_i = 1400$ Btu/hr sq ft °F

$r_{fi} = 0.0005$ hr sq ft °F/Btu

$U_c = U_i = 17.5$ Btu/hr sq ft °F

$\dot{Q} = 3000$ Btu/hr sq ft

$T_\infty = 560$°F

Three cooling schemes will be considered: a) the coolant undergoes a phase change; b) single-phase coolant in parallel flow; and c) single-phase coolant in counterflow.

a) For a phase change coolant

$T_i = 580$°F = constant and $\gamma = 0$

The following parameters can be calculated

$C_\infty = 30,000$ Btu/hr°F

$\beta = -500 \qquad \epsilon = 0.5 \qquad \delta = 0.354 \qquad \alpha = 116.7$

The reactant gas temperature is given by eq. (46).

$$\theta_\infty = -2.52\ (1 - \epsilon^{-116.7})$$

At $\quad X = 1.0 \quad \theta_\infty = \theta_{\infty 2} = -2.52$

Therefore,

$$T_{\infty 2} = 560 + (-20)(-2.52) = 610.3°F$$

T_∞ and T_i are plotted in Figure 4 as a function of χ.

b) Parallel flow heat exchanger utilizing a single-phase coolant. Select

$$T_{i1} = 460°F \,, \quad C_{pi} = 1.0 \text{ Btu/lb °F}$$

$$\dot{m}_i = 10^6 \text{ lb/hr}$$

$$C_i = 10^6 \text{ Btu/hr °F}, \quad \gamma = 0.03$$

$$\beta = 100, \quad \epsilon = 0.5, \quad \delta = 0.35, \quad \alpha = 120.2$$

Using eq. (46) the reactant gas temperature is

$$\theta_\infty = 0.971 \left[1.5\,\chi - 0.709\,(1 - e^{-120.2\,\chi}) \right]$$

At $\quad \chi = 1 \,, \quad \theta_\infty = \theta_{\infty 2} = 0.791$

Therefore,

$$T_{\infty 2} = 560 + (100)(0.791) = 639°F$$

Using eq. (47) the coolant temperature is

$$\theta_i = 0.029 \left[50\,\chi + 0.709\,(1 - e^{-120.2} \quad) \right]$$

At

$$\chi = 1, \quad \theta_i = \theta_{i2} = 1.471$$

Therefore,

$$T_{i2} = 460 + 1.471\,(100) = 607°F$$

T_∞ and T_i are plotted in Figure 5 as a function of χ .

c) Counterflow heat exchanger utilizing a single-phase coolant. The same coolant conditions as used for part (b) are also used here. Note that γ must be evaluated using eq. (48).

T_{i2} = 460°F (coolant inlet temperature)

$$C_i = 10^6 \text{ Btu/hr °F}, \qquad \gamma = -0.03$$

$$\epsilon = 0.5, \qquad \delta = 0.359, \qquad \alpha = 113.2$$

In this case β cannot be immediately calculated since T_{i1} (the coolant outlet temperature for the counterflow case) is not known. At $\chi = 1$, $\alpha\chi = 113.2 >> 10$ and eq. (51) can be used to calculate $T_{\infty 2}$.

$$T_{\infty 2} = T_{i2} + \frac{\dot{Q}}{U}\left[\frac{S_c}{S_o}\left(\frac{1}{1+\gamma}\right) - \frac{U_c}{h}\right]$$

$$= 460 + \frac{3000}{35}\ [.5 \times 1.031 - 17.5/120]$$

$$= 491.7°\text{F}$$

Evaluating eq. (46) at $\chi = 1$,

$$\Theta_{\infty 2} = \left(\frac{1}{1+\gamma}\right)\left[\epsilon\gamma\beta + \frac{\beta\delta}{\alpha} - 1\right].$$

From eqs. (34) and (43)

$$\Theta_{\infty 2} = (T_{\infty 2} - T_{\infty 1})\ C_\infty \beta/\dot{Q}S_o$$

The above two equations can be solved for $\beta = -193.2$

The corresponding equations for Θ_∞, eq. (46), and Θ_i, eq. (47) become respectively,

$$\Theta_\infty = 1.031\left[2.90\ \chi - 1.61\left(1 - e^{-113.2\chi}\right)\right]$$

and

$$\Theta_i = (-0.03)\left[-96.6\chi + 1.61\left(1 - e^{-113.2\chi}\right)\right]$$

The coolant outlet temperature, T_{i1}, can be calculated using eq. (34) and is

$$T_{i1} = T_{\infty 1} - \dot{Q}S_o/C_{\infty}\beta$$

$$= 560 - (-51.7) = 611.7°F$$

T_{∞} and T_i are plotted in Figure 6 as a function of X

Of the three coolant schemes examined in this example, only the phase change coolant maintained the reactant gas temperature in the specified range. In the other two cases, increasing the coolant flow rate would decrease the temperature variation of the fluids.

Discussion

An examination of the results of the above example reveals some of the unique features of this type of heat exchanger. Temperature crossover is possible. The temperature of the hot fluid can be reduced by increasing the thermal resistance on the hot fluid side, 1/h, eq. (51).

The equations developed in this paper can be used for the thermal design of a component which performs the dual functions of a chemical reactor and a heat exchanger. The type of catalytic reactor-heat exchanger analyzed has the potential of providing excellent control of the temperature of the reacting gas.

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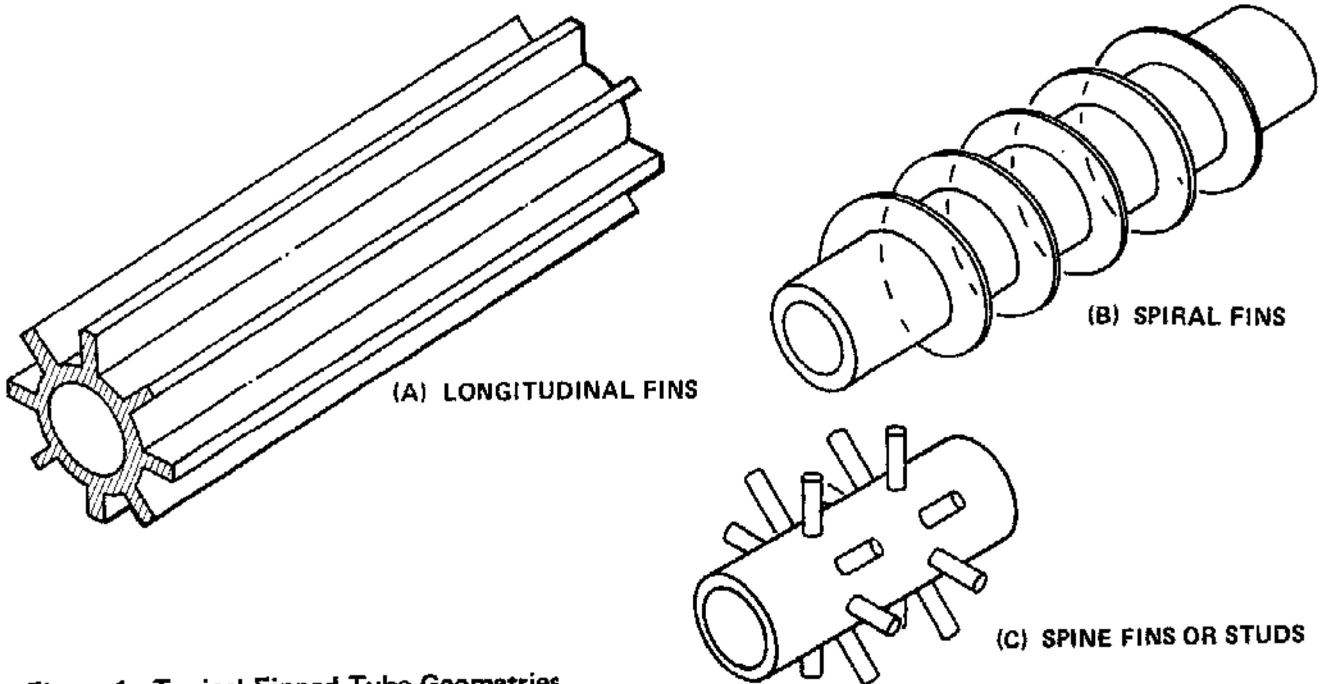


Figure 1 - Typical Finned-Tube Geometries

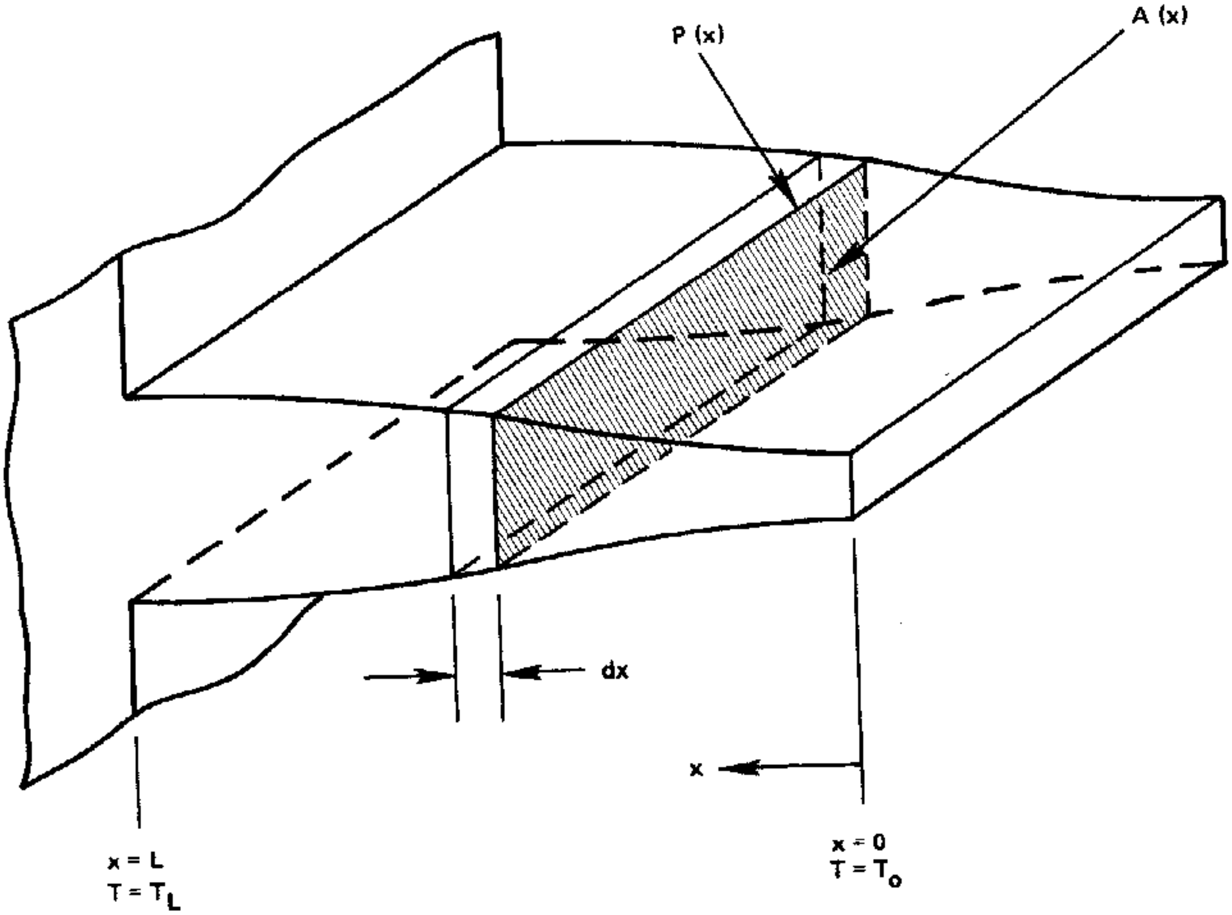
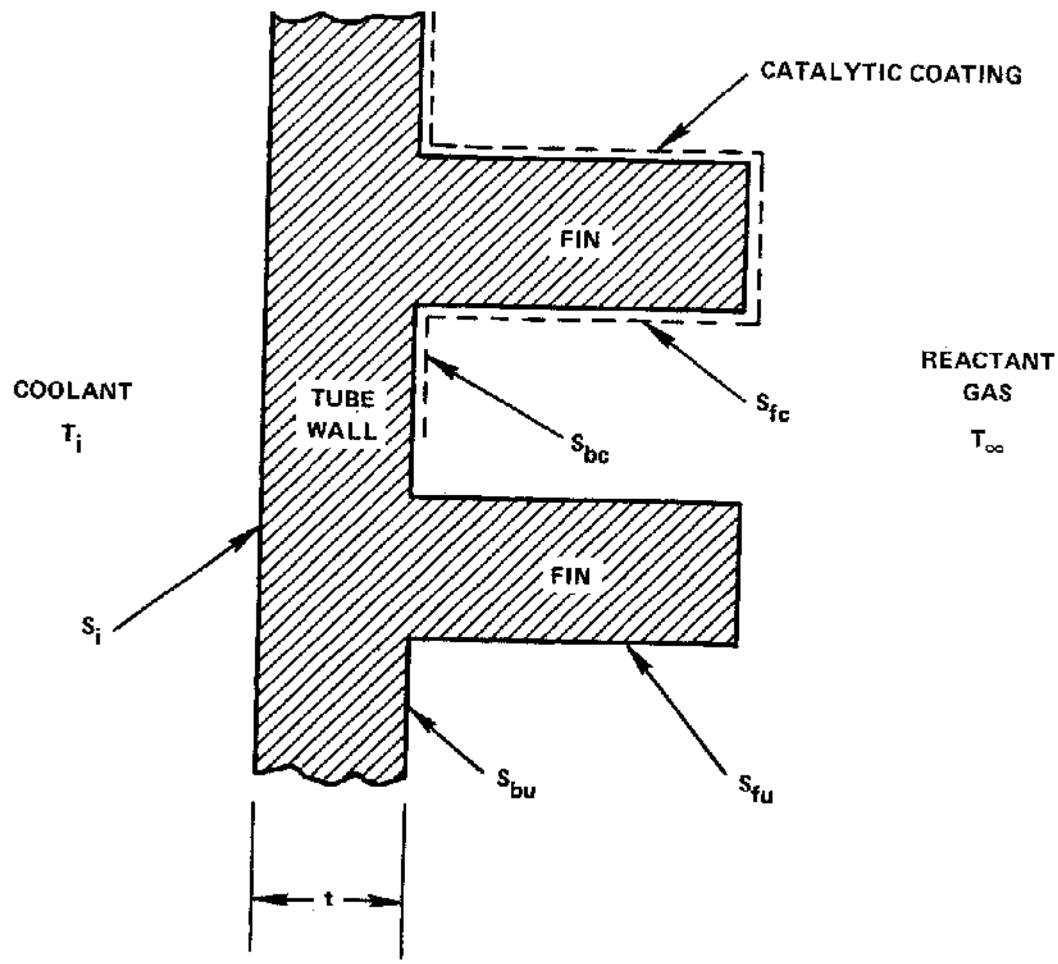


Figure 2 - Fin of Arbitrary Geometry



S_i = TUBE INSIDE SURFACE AREA
S_{fc} = SURFACE AREA OF FINS HAVING CATALYTIC COATING
S_{bc} = OUTSIDE SURFACE AREA OF TUBE HAVING CATALYTIC COATING
S_{fu} = SURFACE AREA OF UNCOATED FINS
S_{bu} = OUTSIDE SURFACE AREA OF UNCOATED TUBE
S_o = TOTAL OUTSIDE SURFACE AREA
$= S_{bc} + S_{fc} + S_{bu} + S_{fu}$

Figure 3 - Section of Generalized Catalytic Heat Exchanger Tube

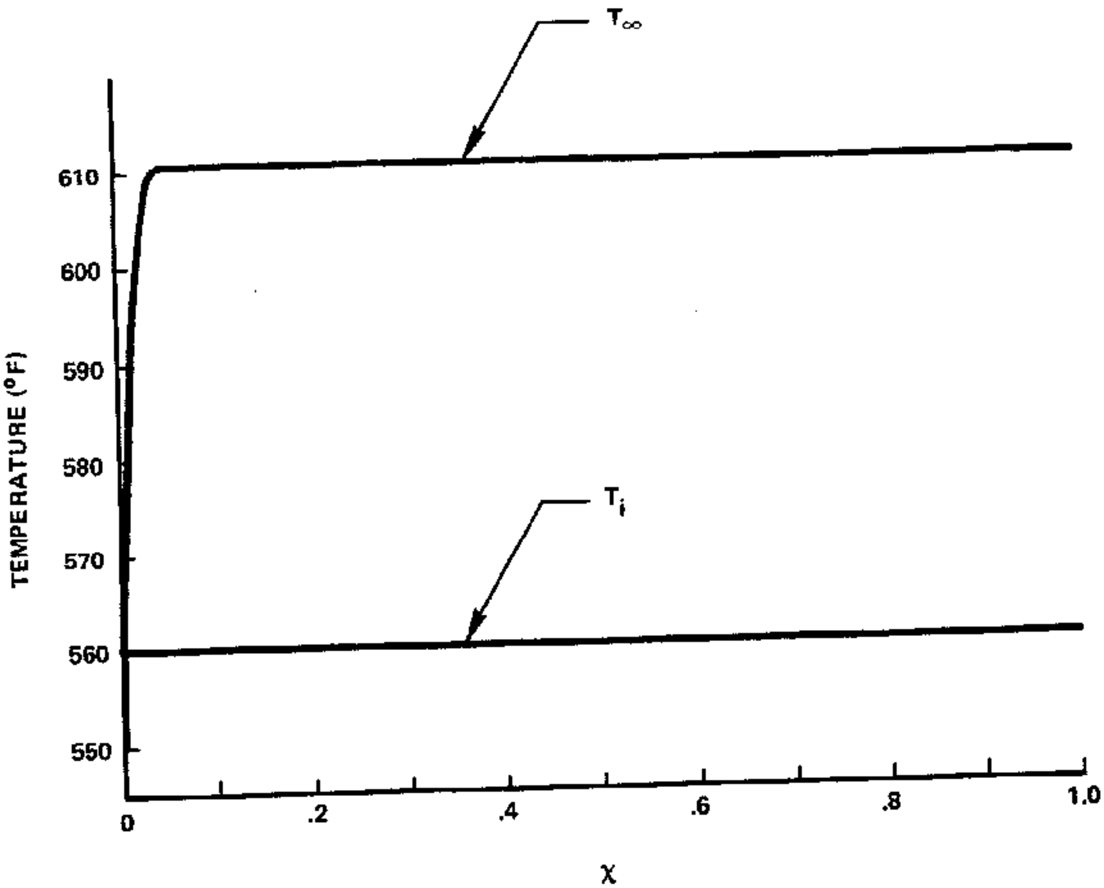


Figure 4 - Temperature Distributions in Heat Exchanger of Example Problem Using a Phase Change Coolant (γ = 0)

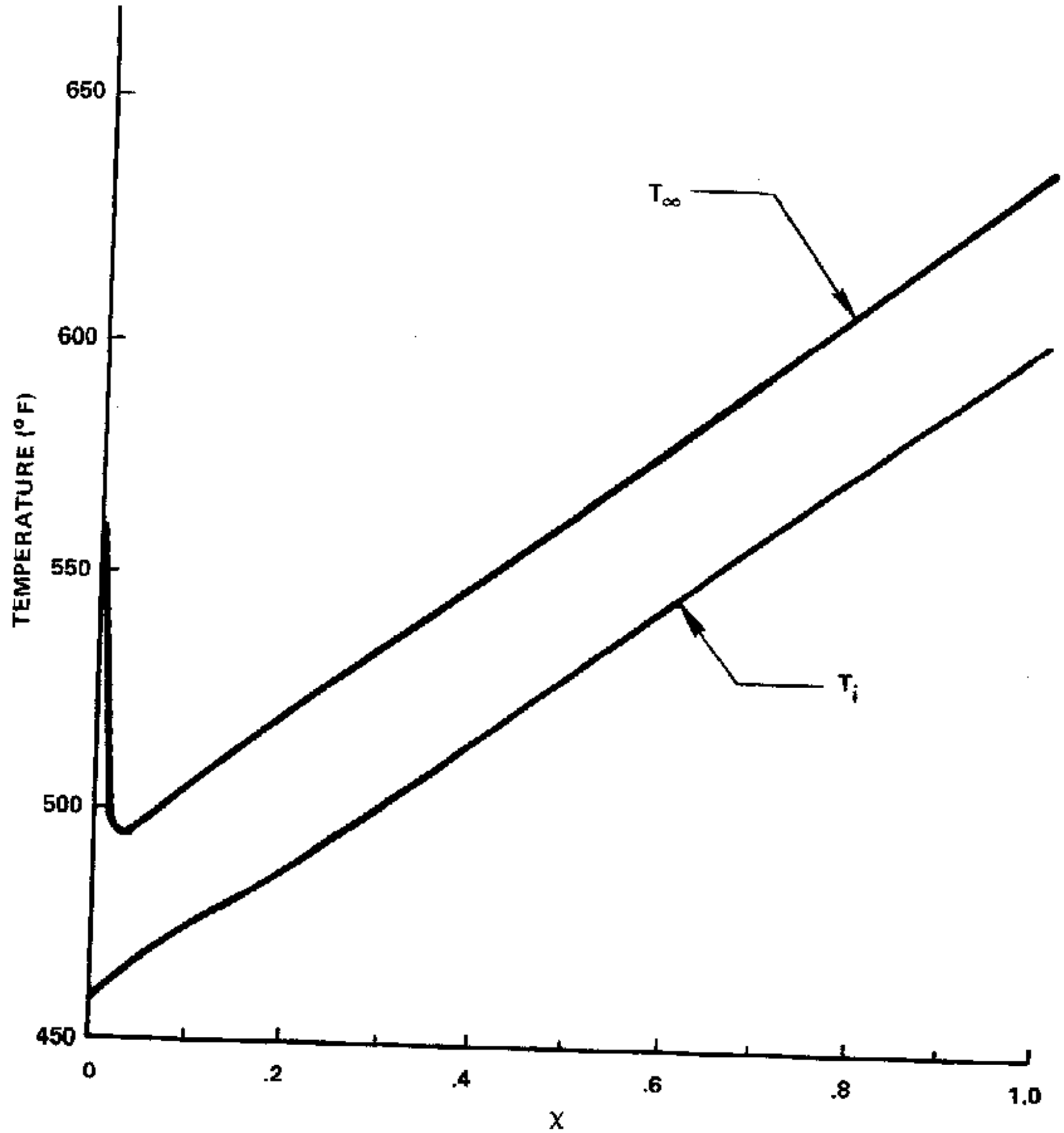


Figure 5 - Temperature Distributions in Heat Exchanger of Example Problem Using the Parallel Flow Configuration (γ = .03)

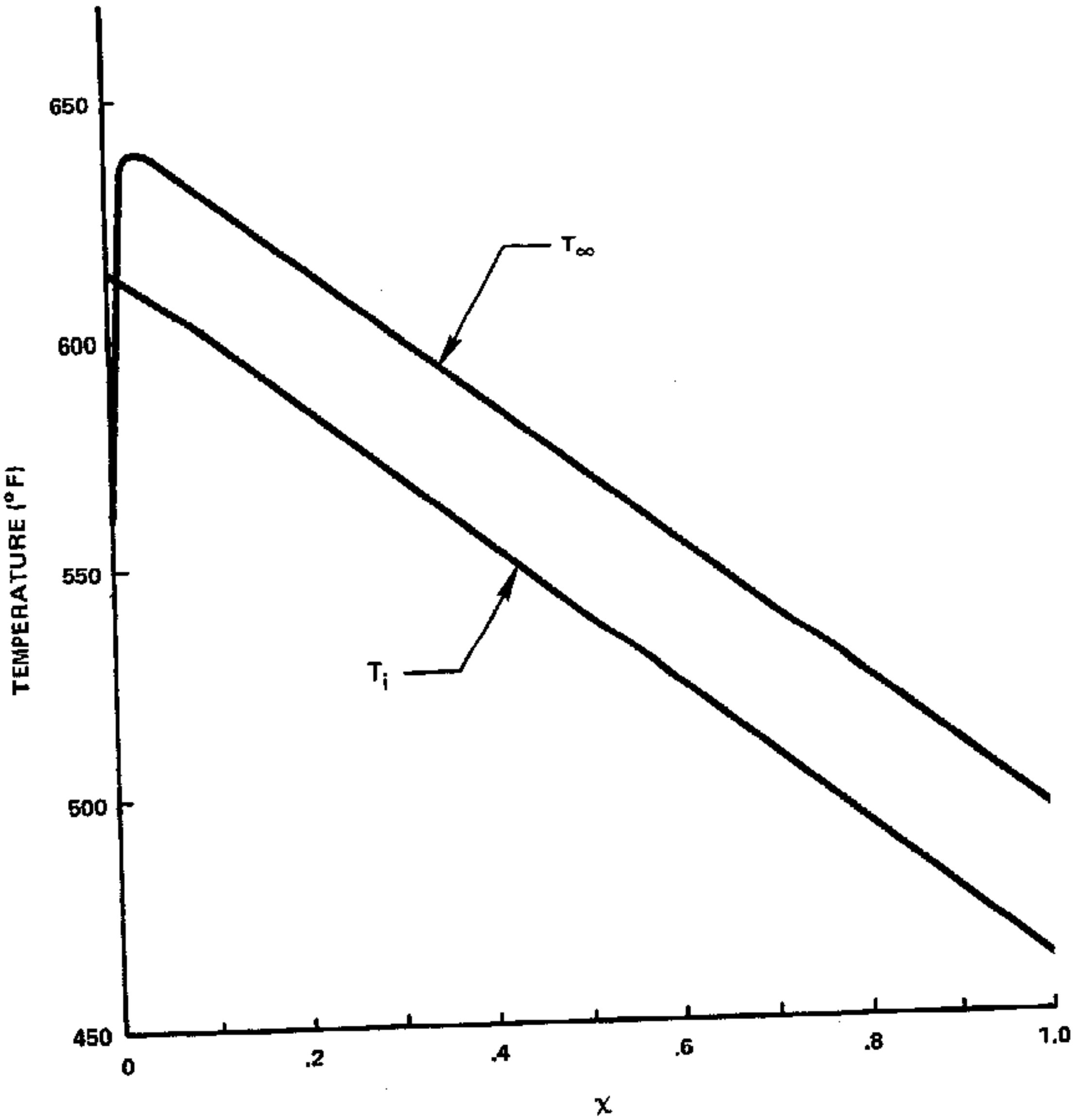


Figure 6 - Temperature Distributions in Heat Exchanger of Example Problem Using the Counterflow Configuration ($\gamma = -.03$)