HEAT TRANSFER ANALYSIS AND DESIGN OF A PLUGGING INDICATOR SYSTEM FOR SRE

by
H. L. Slatten

INTRODUCTION

A general transient heat transfer analysis has been performed on a sodium plugging indicator system comprising a counterflow, concentric-pipe economizer, heat exchanger, flowmeter, plug, and connecting pipe. The entire system is assumed to be at some initial temperature equal to the inlet sodium temperature and suddenly loses heat to some medium in the heat exchanger. While sodium at a constant temperature enters the plugging indicator system from the main sodium line of the SRE loop, heat is removed by the heat exchanger reducing the heat stored in the sodium and components and lowering the temperature at the plug. The rate at which the minimum temperature at the plug decreases is of primary interest for two reasons: (1) It is desirable to reduce the sodium temperature to the plugging temperature in a reasonable short time. (2) Once the plugging temperature range is approached, the rate of change should be small to make it possible to detect the plugging temperature accurately.

The particular requirements of the plugging indicator system have been suggested in an IOL from D. L. Condotta to D. T. Eggen on March 7, 1955. On the basis of these suggestions the system is designed to be capable of cooling 1 gpm of sodium from 750°F to any plugging temperature. The design has a wide range of control of the time rate of change of sodium temperature; in the range from 500-300°F a rate of 5°F/min or less is obtainable. At the plugging temperature cooling may be interrupted to produce an immediate reversal of temperature change at the plug. To meet these requirements, gas (specifically nitrogen in the galleries) with forced convection has been selected as the heat exchange medium.

RESULTS

A design for a plugging indicator system is that based upon conclusions reached by the general analysis given in the Appendix. The design and operating data is presented in Table I. A schematic sketch of the design is shown in Fig. 1.
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and a detail drawing of a cross section of the heat exchanger is given in Fig. 2. A typical cooling rate curve for the system where the nitrogen flow rate is decreased from 365 cfm to 70 cfm when the minimum (or plug) temperature reaches 400°F is shown in Fig. 3. A blower capacity of 500 cfm is specified enabling a more rapid initial cooling rate than is shown in the figure. The outside of the duct covering the heat exchanger, as well as the other components in the system, should be insulated so that there will be a minimum of cooling and temperature drop during unplugging and cleaning.

The design consists of a U-type economizer having concentric pipes. Its shell is a 1-1/4 inch standard 304 stainless steel pipe. The inner tube is also 304 stainless steel and has a 1 inch outside diameter with a 35 mil wall thickness. The economizer may be designed similarly with the SRE cold trap economizers. The heat exchanger consists of a bank of 6 parallel longitudinal finned tubes of 3/4 inch standard pipe each 2 feet long, enclosed in a suitable duct that may be a pentagon in cross section as shown in Fig. 2. The fins are placed longitudinally to accommodate a "Calrod" type heater for thawing frozen sodium, for preheating, or for producing a rapid reversal of temperature change at the plug during incipient plugging. The fins are stainless steel and are welded to the pipe to insure that melting of fin material or bond between fin and pipe will not occur at the highest temperatures of operation. There are 14 fins per tube, spaced 24° apart, each 1/16 inch thick and 1/2 inch long. An equivalent standard finned tube may be substituted; however, the thermal capacity of the system must remain at 15 Btu/°F to preserve the same transient behavior. A variable speed drive for supplying from 0 to 500 cfm over the ducted finned tubes is required. The pressurehead required of the fan is not specified, since the relative position of the fan and heat exchanger is not yet known. The fan and motor might be placed outside of the gallery using air cooling if placing them in the gallery is objectionable.

**TABLE I**

<table>
<thead>
<tr>
<th>Design Data</th>
<th>Economizer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>sodium-to-sodium, counterflow, concentric pipe</td>
</tr>
<tr>
<td>Shell</td>
<td>1-1/4 inch standard 304 stainless steel pipe</td>
</tr>
<tr>
<td>Inner tube</td>
<td>1 inch OD, 0.035 inch wall, 304 stainless steel</td>
</tr>
<tr>
<td>Length</td>
<td>6 feet plus 180° standard weight, long radius return</td>
</tr>
<tr>
<td>Annular flow area</td>
<td>[0.711 \text{ in}^2]</td>
</tr>
</tbody>
</table>
Economizer (Continued)

<table>
<thead>
<tr>
<th>Inside flow area</th>
<th>0.680 in²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annular sodium velocity</td>
<td>0.451 ft/sec</td>
</tr>
<tr>
<td>Inside sodium velocity</td>
<td>0.472 ft/sec</td>
</tr>
<tr>
<td>Overall heat transfer coefficient</td>
<td>960 Btu/hr-ft²</td>
</tr>
<tr>
<td>Thermal capacitance, inc. sodium</td>
<td>~3.43 Btu/°F</td>
</tr>
</tbody>
</table>

Heat Exchanger:

- Type: sodium-to-nitrogen, longitudinal finned tube, counterflow
- Number of parallel tubes: 6
- Tube: 3/4 inch standard pipe, 304 stainless steel
- Fins: 1/16 inch thick, 1/2 inch long, 304 stainless steel welded
- Length: 2 feet of finned surface
- Number of fins: 14 per tube
- Fin spacing: 24°
- Inside heat transfer area: 2.59 ft²
- Ratio of outside area to inside area: 8.31
- Nitrogen flow area: 21.8 in²
- Nitrogen heat transfer coeff. at 40 ft/sec: 10.2 Btu/hr-ft²°F
- Fin effectiveness: 82.3%
- Overall heat transfer coeff. based on inside area: 69.5 Btu/hr-ft²°F
- Blower capacity: 0-500 cfm

Operating Data

Constants

<table>
<thead>
<tr>
<th>Sodium flow rate</th>
<th>1 gpm, 450 lb/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet sodium temperature</td>
<td>750° F</td>
</tr>
<tr>
<td>Nitrogen pressure</td>
<td>~1 atm</td>
</tr>
<tr>
<td>Nitrogen temperature</td>
<td>150° F</td>
</tr>
</tbody>
</table>

Steady State

<table>
<thead>
<tr>
<th>Minimum sodium temperature</th>
<th>250° F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economizer parameter, ( \frac{U_1 A_1}{V_C} ), (Ratio of temp. drop to temp. approach)</td>
<td>10</td>
</tr>
<tr>
<td>Temperature approach in economizer</td>
<td>~45° F</td>
</tr>
</tbody>
</table>

*An equivalent finned tube heat exchanger may be substituted.

**Other steady state minimum temperatures can be obtained by varying cooling.
Nitrogen velocity thru heat exchanger ............ 7.8 ft/sec
Nitrogen flow ........................................ 70 cfm
Heat exchanger parameter, $U_{2A_2}/wc$, (ratio of temp. drop to mean temp. diff.) ................ 0.37
Heat loss to nitrogen .................................. 1.9 kW

Transient State (Typical Case, see Fig. 3)
A. Plug temp. range 750 - 400° F
   Initial system temperature ....................... 750° F
   Nitrogen velocity thru heat exchanger .......... 40 ft/sec
   Nitrogen flow ...................................... 365 cfm
   Heat exchanger parameter, $U_{2A_2}/wc$ ........ 1.1
   Initial rate of temp. change at plug .......... -31.7°F/min
   Rate of temp. change at plug at 400° F .......... -12.5°F/min
   Time required to drop temp. to 500° F .......... 16 min.
B. Plug temp. < 400° F
   Nitrogen velocity thru heat exchanger .......... 7.8 ft/sec
   Nitrogen flow ...................................... 70 cfm
   Heat exchanger parameter, $U_{2A_2}/wc$ ........ 0.37
   Rate of temp. change at plug at 400° F .......... 6.4 °F/min
   Rate of temp. change at plug at 300° F .......... 2.1 °F/min
FIG. 1

SODIUM IN
1 GPM
750 °F

ECONOMIZER
1-1/4" STD. PIPE, 1" OD TUBE 0.035 WALL

PLUG FLOWMETER

SHEET STEEL DUCT
LONGITUDINAL FIN HEAT EXCHANGER 6 TUBES IN PARALLEL WITH "CALROD" HEATERS

N₂

BLOWER—0–500 CFM

SCHEMATIC
NOT TO SCALE
FIG. 2

CROSS SECTION OF Na-to-Na "FAT EXCHANGER" LUGGING INDICATOR SYSTEM OF ONE

NORTH AMERICAN AVIATION, INC.
INTERNATIONAL AIRPORT
LOS ANGELES 45, CALIFORNIA

PREPARED BY: HLS
CHECKED BY: 
DATE: 
REPORT NO.
MODEL NO.

FULL SCALE

STAINLESS STEEL LONG 1/4 x 1/2 in.
CALROD TYPE HEATER

3/4" STD. PIPE
OD = .824
ID = .622

SHEET STEEL OUT

2.175
A TYPICAL COOLING RATE CURVE FOR THE PLUGGING INDICATOR SYSTEM OF SRE

FIG. 3

**Conditions**

- Economizer, \( \frac{V}{h} = 10 \)
- Thermal Conductivity, \( q' = 15 \) Btu/hr\(^\circ\)F
- Sodium Flow, \( v = 1 \) gpm

**Initial Temp.**

- Heat Exchanger Outside Area = 21.9 ft\(^2\)
- Heat Exchanger N\(_2\) Flow Area = 21.6 ft\(^2\)

**Equilibrium Temp.**

\[ \frac{U_A}{h} \approx 0.37, \quad N_2 \text{ Flow} = 70 \text{ GFM} \]

**Nitrogen Temp.**

**Time, Minutes**
APPENDIX

Theory

The system is composed of the components in the schematic sketch below.

Considering an energy balance of the entire system, the heat added between 1 and 6 is

\[ w_c \left( T_1 - T_6 \right) \text{ Btu/hr.} \]

The heat added between 3 and 4 is

\[ U_2 A_2 \Delta T_m \]

\[ = U_2 A_2 \left( T_a - \frac{T_3 + T_4}{2} \right) \text{ Btu/hr.} \]

The heat stored in the system is

\[ \frac{d}{d\Theta} \sum_{i=1}^{n} m_i c_i T_i \text{ Btu/hr.} \]

Provided the economizer, plug, flowmeter, and connecting piping is well insulated, the algebraic sum of the heats added as given above is equal to the heat stored, or

\[ w_c \left( T_1 - T_6 \right) + U_2 A_2 \left( T_a - \frac{T_3 + T_4}{2} \right) = \frac{d}{d\Theta} \sum_{i=1}^{n} m_i c_i T_i \quad \ldots \ldots \quad (1) \]
where \( w \) = flow rate of sodium, lb/hr

\( c = \text{specific heat of sodium, Btu/lb·°F} \)

\( T_1 = \text{inlet temp. to economizer, °F} \)

\( T_6 = \text{outlet temp. from economizer, °F} \)

\( U_2 = \text{overall heat transfer coeff. of heat exchanger, Btu/hr·°F} \)

\( A_2 = \text{heat transfer area of heat exchanger, ft}^2 \)

\( T_a = \text{temp. of medium cooling heat exchanger, °F} \)

\( T_3 = \text{inlet sodium temp. to heat exchanger, °F} \)

\( T_4 = \text{outlet sodium temp. from heat exchanger, °F} \)

\( \Theta = \text{time, hours} \)

\( m_1 = \text{mass of sodium or metal in ith component, lb} \)

\( c_i = \text{specific heat of sodium or metal in ith component, Btu/lb·°F} \)

\( T_i = \text{temperature of sodium or metal in ith component, °F} \)

The storage term on the right in Eq. (1) may be simplified by writing

\[
\sum_{i=1}^{n} m_i c_i \frac{dT_i}{d\Theta} = C \frac{dT_{av}}{d\Theta} \quad \ldots \ldots \ (2)
\]

where \( C \) is the total thermal capacitance of the entire system and \( T_{av} \) is a weighted average temperature defined by

\[
T_{av} = \frac{\sum_{i=1}^{n} m_i c_i T_i}{\sum_{i=1}^{n} m_i c_i} = \frac{\sum_{i=1}^{n} m_i c_i T_i}{C}
\]

If an arithmetic average temperature, \( \frac{T_1 + T_4}{2} \), is used for the purpose of further simplification, a corresponding hypothetical thermal capacitance defined by the following expression must be introduced.

\[
C' = \frac{T_{av}}{T_1 + T_4 \frac{1}{2}} - C \quad \ldots \ldots \ (3)
\]

Calculation reveals that the ratio of \( C'/C \) is less than unity and about 0.8.

Substituting Eq. (3) into (2) and the result into Eq. (1) and noting that \( T_1 - T_6 = T_2 - T_3 \).
where \( F \) is the fraction of the total temperature drop in the system that occurs in the heat exchanger; that is,

\[
F = \frac{T_3 - T_4}{T_1 - T_4}
\]

Eliminating \( T_2, T_3, \) and \( T_5 \) from Eq. (4) by substituting the expressions above gives,

\[
F (T_4 - T_2) + \frac{U_2 A_2}{wc} \left[ T_4 - T_2 - \frac{F}{2} (T_4 - T_2) \right] = \frac{C'}{2wc} \frac{dT_4}{d\theta} \quad \ldots \quad (5)
\]

Since

\[
wc (T_1 - T_2) = U_1 A_1 (T_2 - T_4)
\]

\[
F = \frac{1}{U_1 A_1 / wc + 1} = \frac{1}{K_1 + 1}
\]

Letting \( \frac{U_2 A_2}{wc} = K_2 \), Eq. (5) becomes

\[
\frac{dT_4}{d\theta} + \frac{2mc}{C'} \left( K_2 + \frac{1}{K_1 + 1} - \frac{1}{2} \frac{K_2}{K_1 + 1} \right) T_4 = \frac{2mc}{C'} \left( K_2 \frac{T_4 - \frac{1}{K_1 + 1} T_1}{K_1 + 1} + \frac{1}{2} \frac{K_2}{K_1 + 1} T_1 \right)
\]

or

\[
\frac{dT_4}{d\theta} + \psi T_4 = \lambda
\]

\[
\ldots \quad (6)
\]

The solution of Eq. (6) for the initial condition,

\[
T_4 = T_1 \text{ when } \theta = 0,
\]

is

\[
T_4 = \frac{\lambda}{\psi} \left( T_1 - \frac{\lambda}{\psi} \right) e^{-\psi \theta}
\]

\[
\ldots \quad (7)
\]
The steady state value of $T_4$ is

$$\lim_{\epsilon \to \infty} T_4 = \frac{\mathcal{K}}{\mathcal{V}'} = \frac{K_2 T_a + \frac{1}{2} K_1 T_1 - \frac{1}{2} K_2}{K_2 + \frac{1}{2} K_1}$$

(3)

Eq. (7) is plotted in Fig. 5 for various values of the hypothetical thermal capacitance, $C'$, an economizer parameter, $\frac{U_1 A_1}{w_c} = 10$, and an equilibrium temperature of $250^\circ F$. The value of the heat exchanger parameter, $\frac{U_1 A_1}{w_c}$, that gives the equilibrium temperature of $250^\circ F$ is obtained by solving for $K_2$ in Eq. (3):

$$K_2 = \frac{T_1 - \frac{\mathcal{K}}{\mathcal{V}'}}{\frac{1}{2} - (K_1 + 1) T_a + (K_1 + \frac{1}{2}) \frac{\mathcal{K}}{\mathcal{V}'}}$$

(9)

Eq. (9) is plotted in Fig. 6 for an equilibrium temperature, $\frac{\mathcal{K}}{\mathcal{V}'} = 250^\circ F$.

Eq. (7) is also represented in Fig. 5 showing the effect of varying the economizer parameter, $\frac{U_1 A_1}{w_c}$, on the change in plug temperature, $T_4$, with time, holding the equilibrium temperature constant at $250^\circ F$.

**Conclusions**

Several conclusions may be drawn from the general analysis. For a fixed system to cool from $750^\circ F$ at the plug to the plugging temperature (presumably in the range $300-500^\circ F$) in a reasonable length of time either the thermal capacitance (mass x specific heat) of the system must be extremely small or the temperature drop that occurs in the heat exchanger at equilibrium must be a large fraction of the total drop. These facts are seen clearly in Figs. 4 and 5, respectively.

Further, when the time required to cool down to the plugging temperature range is reasonably small, the rate at which the temperature is changing is too large to get an accurate reading of the plugging temperature. Apparently some method is required to decrease the rate of cooling once the plugging temperature
range is approached. The best method of control is to vary the heat exchanger parameter, $U_2 A_2/w_c$. A wide range of control can be obtained in this parameter if a gas is used as the coolant because it would be the controlling resistance making up the overall heat transfer coefficient, $U_2$. This is done very effectively by changing the gas velocity.

Figure 5 indicates that a large value of the economizer parameter, $U_1 A_1/w_c$, is required to obtain a low cooling rate in the plugging range. The corresponding value of the heat exchanger parameter indicated must be increased by three or four times to obtain a reasonably rapid initial cooling rate.

Distribution: SRE
Condotta, D. L.
Cyganski, R.
Trilling, C. A.
Sletten, H. L.
TIME VARIATION OF FLUID HEATING SYSTEM MINIMUM TEMPERATURE FOR VARIOUS VALUES OF SYSTEM THERMAL CAPACITANCE AND A CONSTANT EQUILIBRIUM TEMPERATURE

FIG. 1

ECONOMIZER, $\frac{Q_A}{\Delta T_F} = 10$

HEAT EXCHANGER, $\frac{Q_A}{\Delta T_F} = 0.173$

MINIMUM TEMPERATURE, $T_{\text{min}}$

EQUILIBRIUM TEMPERATURE

COOLANT TEMPERATURE

TIME, MINUTES

$\frac{Q_A}{\Delta T_F}$
Fig. 5

System thermal capacitance = 10 Btu/°F

Initial temp.

Minimum temperature, °F

10 = \( \frac{U A}{W C} \) of economizer

7

0.370 = \( \frac{U A}{W C} \) of heat exchanger

4

0.476

300

1

0.667

Equilibrium temp.

200

Coolant temp.

100

0

0 20 40 60 80 100 120 140 160

Time, minutes
VARIATION IN HEAT EXCHANGER PARAMETER
WITH ECONOMIZER PARAMETER FOR A CONSTANT
EQUILIBRIUM MINIMUM TEMPERATURE OF
250°F AND A CONSTANT INLET TEMPERATURE
OF 750°F

FIG. 6