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TITULO HEAT TRANSFER IN HOT OIL PIPELINE

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ABSTRACT

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This paper deals with heat loss which is one of the major problems in engineering of hot oil pipelines the need for which has been increasing in these recent years. Success in design of pipelines conveying heavy crude oil or heavy fuel oil depends largely on optimization of pipe diameter, pumping power and oil temperature.

Hot oil pipeline system can be one solution of such optimization if the system is designed on the basis of proper assumptions which in turn must be based on accurate analysis of heat loss from the pipeline. This presents a significant design problem particularly in the case of a long pipeline which is subject to varying climatic conditions and which necessarily casuses the system to become complicated. This paper presents the results of analysis on variation of heat loss as obtained by the use of simulation models, and verification of the adequacy of such analysis by means of experimental studies.

For this sort of problem, a final solution should be obtained by testing the specimen pipeline structure under actual conditions; however, the method of analysis as introduced in this paper is believed to serve the purpose effectively at the early planning stage of the system.

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Introduction

Among a variety of petroleum oils, heavy fuel oil and heavy crude oil cannot usually be forced to flow by pumping under normal atmospheric temperature because of their high viscosity. In order to insure satisfactory flow, such oils must generally be heated to temperatures ranging from 60°c to 100°c in a pumping station located at the starting point of a pipeline system. If such a pipeline is subject to a great heat loss, a system becomes uneconomical because reheating stations must be provided at short intervals. In designing this type of pipelines, therefore, effective thermal insulation is a matter of prime importance.

Various means have been developed to prevent high viscosity oils from becoming too viscous to flow satisfactorily in pipelines and to avoid the lowering of pumping efficiency. Such means may generally be categorized as: heating method, replacement method, and additive introduction method.

Of the foregoing three, the heating method may be considered the safest, most reliable and most effective for pipelines handling heavy crude oil provided that proper thermal insulation is effected with reasonable economy. As recent progress in manufacture and application of foamed polyurethane has made it possible to effect efficient pipeline insulation, an increasing number of oil pipelines have come to be planned and constructed by using the heating method.

To optimize the design of a heated oil pipeline, the factors as given in the following table should be considered:

Table 1 Changes for Design Optimization of Pipeline System Elements and Their Effects

Changes in Design of Elements	Initial Cost	Operation and Maintenance Costs
* Increase in pipe diam.	* Pipeline cost will increase. * Pumping power cost will decrease. * Construction cost for pump station per horsepower will remain constant.	* Operation and maintenance costs will increase. * Heating fuel cost will remain constant. * Energy cost for pumping will decrease. * Other operation and maintenance costs will decrease.
* Increase in pumping power	* Construction cost for pump station per horsepower will remain constant. * Pipeline cost will decrease.	* Heating fuel cost will remain constant. * Pumping energy cost will increase. * Other operation and maintenance costs required for pump station will decrease. * Operation and maintenance costs will decrease.
* Increase in oil temperature	* Pumping power cost will decrease. * Construction cost per pump station per horsepower will increase. * Pipeline cost will remain constant.	* Heating fuel cost will increase. * Pumping energy cost will decrease. * Other operation and maintenance costs required for pump station will decrease. * Operation and maintenance cost for pipeline will remain constant.

As can be known from the table, efficient insulation of a pipeline depends largely on its thermal insulation.

A large number of research papers have been published in these past years discussing problems of heat loss from heated oil pipelines. In this paper, the authors will describe some findings on the heat loss from the pipeline support structure as obtained by the analysis and experiment of two support structure models. While analyses of heat loss from a pipeline itself may be made by the use of a rather simple model, those of heat loss from support structures generally require more complicated models because of varying types of support structures that can be designed. For this reason, the effectiveness of thermal insulation for pipe support is greatly affected by whether or not a model is properly simulated for each support system which is to be designed.

1 Setting up Models

A variety of hot oil pipeline supports has been devised in the past; those shown in Fig. 1 represent some examples designed by a certain Soviet research station.

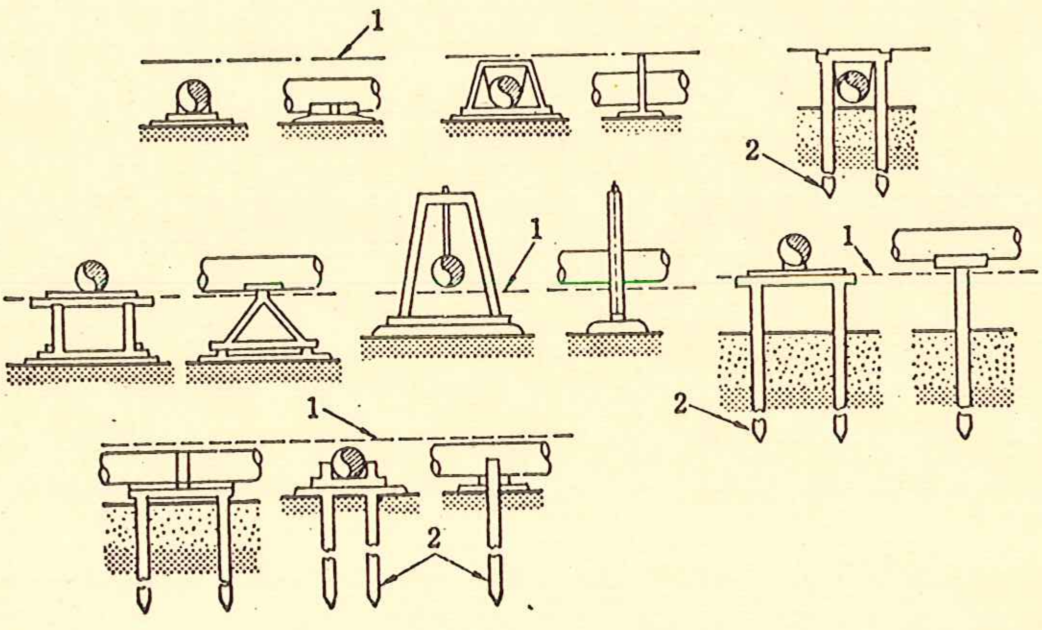


Fig. 1

In any case, insulation of the support structure must be extended as close to the pipe itself as practicable. On the other hand, there are some structural requirements which must be taken into account. They include:

(1) weight of pipe

(2) weight of oil contained in pipe

(3) weight of snow and ice

(4) wind pressure

(5) seismic force, and

(6) loads due to movements of pipe as caused by thermal effects or by oil pressure built up in pipe by pumping

It goes without saying that pipe structures should be designed to withstand probable combination of the loads and force described above. The analysis described in this paper involves two types of models as shown in Fig. 2: one is for the case where a clamp holding the pipe section is directly supported by two legs; and the other if for the case where the clamp is supported by a beam which in turn is supported by the legs.

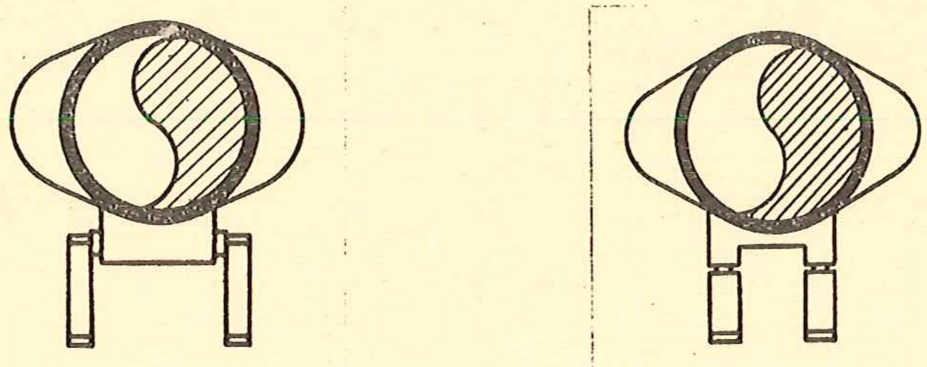


Fig. 2

1.1 Brief Description of Models

Both in Model A and in Model B, the shaft pin acting as support element is surrounded by high strength resin as shown in Fig. 3 in order to reduce heat transfer.

Further, the shaft is housed in a fiber-reinforced plastic cover into which foamed polyurethane is poured.

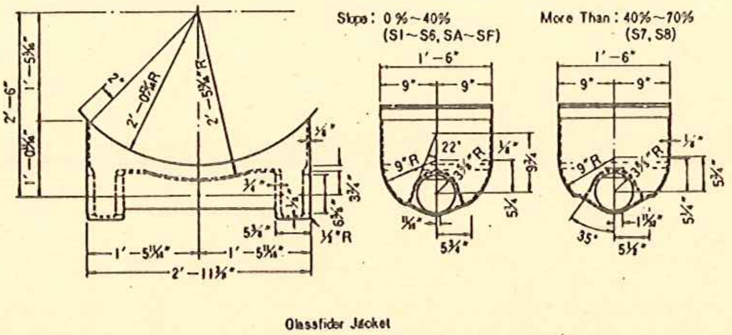


Fig. 3

1.2 Heat Loss Analyses

(Comparison of Model A with Model B)

The heat transfer formula and temperature conditions as used for the present analyses were as follows:

Table 2 Heat Transfer Formula

$$Q = \frac{A(Qo - Qr)}{\frac{t}{\lambda} + \frac{1}{\alpha}}$$

Where,

Q = heat dissipation (kcal/hr)

A = surface area (m^2)

Qo = inside temperature (62.8°c)

Qr = atmospheric temperature (-49.7°c)

t = thickness of insulating material (m)

λ = coefficient of heat conductivity for insulating material (0.01736 kcal/mhr°c)

α = coefficient of surface heat conductivity (23.4 kcal/m^2hr°c)

The values given in Table 3 represent heat losses for Model A and Model B. The studies have indicated preference of Model B with respect to the heat loss. This may be ascribed to the fact that Model B is smaller than Model A both in surface area and in busing-to-sleeve contact area (see Fig. 4).

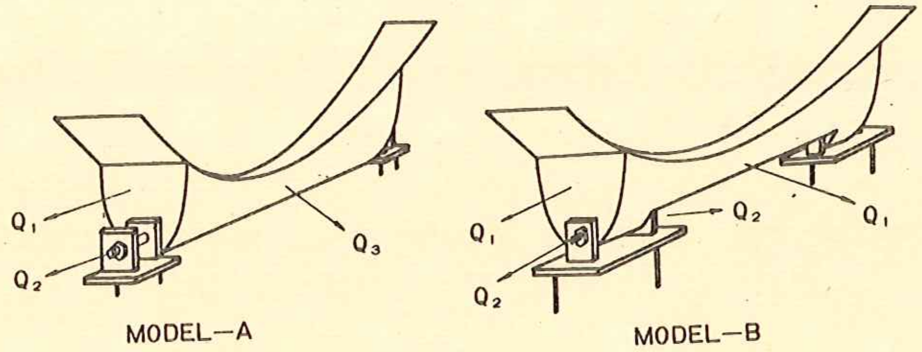


Fig. 4

Table 3 Heat Loss Comparison for Models A and B

Heat Loss	Model A	Model B
Q_1 Cover Surface	31.7 Kcal/hr (125.7 BTU/hr)	27 Kcal/hr (107.1 BTU/hr)
Q_2 Pivot Pin	74.4 Kcal/hr (295.0 BTU/hr)	61 Kcal/hr (241.9 BTU/hr)
Total Heat Loss from One Basket Insulation	106.1 Kcal/hr (420.7 BTU/hr)	88 Kcal/hr (349.0 BTU/hr)
Total Heat Loss from One Support Structure	212.2 Kcal/hr (841.4 BTU/hr)	176 Kcal/hr (698.0 BTU/hr)

The details of calculation are as per the following pages.

In addition, a performance test has been conducted to obtain actual heat loss figures in such a manner as described in the section 5.

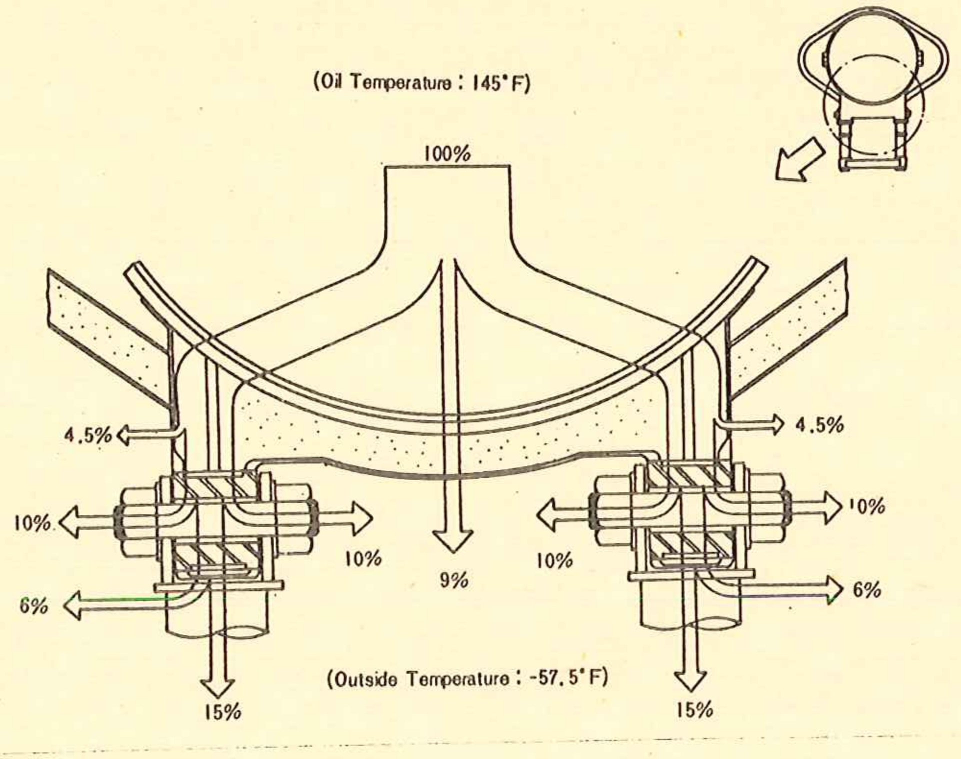


Fig. 5 Heat Flow through Pin and Cover Insulation

2 Heat Calculation - Model A

Purpose of calculation : to obtain heat loss figures from a support structure.

2.1 Heat Loss From Pivot Pin

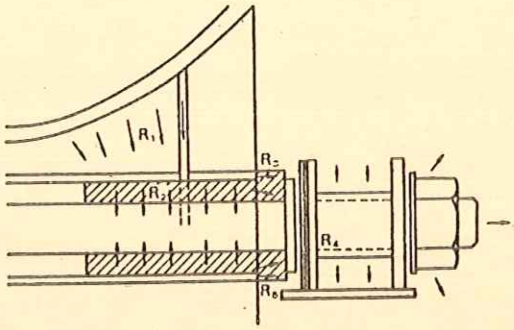


Fig. 6

a) R_1 (Heat Resistance of Rib)

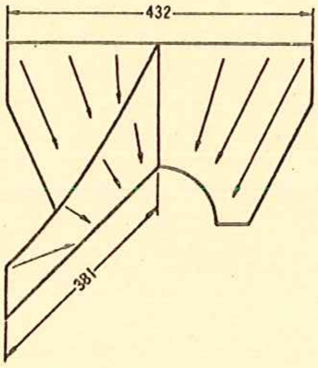


Fig. 7

Average cross sectional area of heat flow route (S)	= 0.00782 (m^2)
Average distance of heat flow route (t)	= 0.152 (m)
Thermal conductivity of rib (λ)	= 45 (Kcal/m·hr·c)

$$R_1 = \frac{t}{s\lambda}$$

$$= \frac{0.152}{0.00782 \times 45}$$

$$= 0.432$$

b) R_2 (Heat Resistance of Bushing against Heat Flow to Pivot Pin)

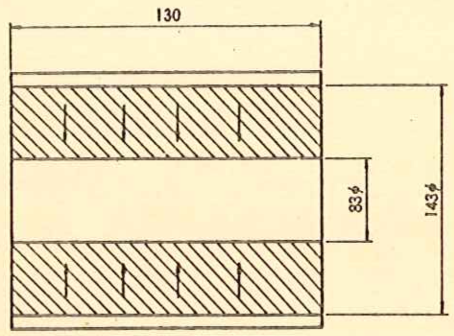


Fig. 8

$$R_2 = \frac{1}{2\pi\lambda L} \log \frac{d_2}{d_1}$$

$$= \frac{1}{2 \times 3.14 \times 0.248 \times 0.13}$$

$$\times \log \frac{0.143}{0.083}$$

$$\doteq 2.686$$

c) R_3 (Heat Resistance of Bushing against Heat Flow Parallel to Axis)

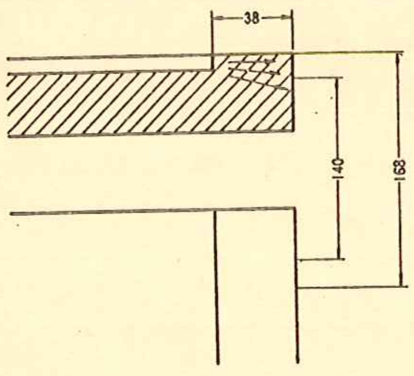


Fig. 9

$$S = \frac{\pi}{4} (0.168 - 0.140) \times \frac{1}{2}$$

$$= 0.00339$$

$$R_3 = \frac{0.038}{0.00339 \times 0.248}$$

$$= 45.199$$

d) R_4 (Heat Resistance against Heat Flow from Metal Plate to Support)

$$R_4 = \frac{0.081}{2 \times 0.018 \times 0.162 \times 45}$$

$$= 0.309$$

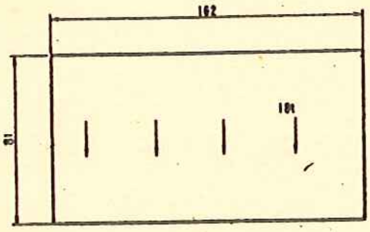


Fig. 10

e) R_5 (equal to R_3)

$R_5 = 45.199$

f) R_6 (Surface Heat Resistance)

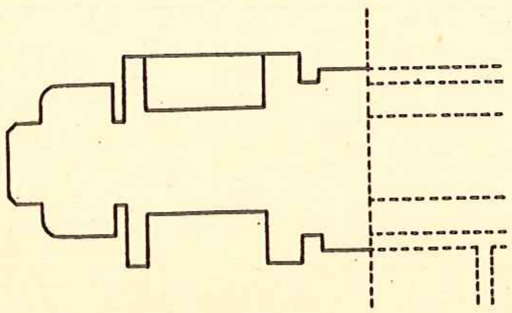


Fig. 11

S : surface area indicated with solid lines

$= 0.179\ (m^2)$

α : surface thermal conductance

$= 23.4\ (kcal/m^2 \cdot hr \cdot {}^\circ c)$

$$R = \frac{1}{S\alpha} = \frac{1}{0.179 \times 23.4}$$

$$= 0.239$$

From the foregoing calculations a) thro' f), it follows:

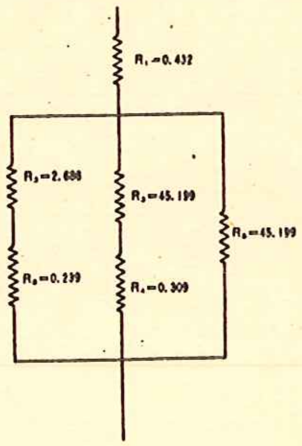
$R_{26} = R_2 + R_6$

$= 2.686 + 0.239 = 2.925$

$R_{34} = R_3 + R_4$

$= 45.199 + 0.309 = 45.508$

$R_5 = 45.199$



$$\frac{1}{R_{23456}} = \frac{1}{R_{26}} + \frac{1}{R_{34}} + \frac{1}{R_{5}}$$

$$= \frac{1}{2.925} + \frac{1}{45.508} + \frac{1}{45.199}$$

$\therefore$ $R_{23456} = 2.591$

Total Heat Resistance $R = R_1 + R_{23456}$

$= 0.432 + 2.591$

$= 3.023$

Total Heat Loss Q $= \frac{(62.8 - (-49.7))}{3.023}$

$= 37.2$ kcal/hr

2.2 Heat Loss From Cover

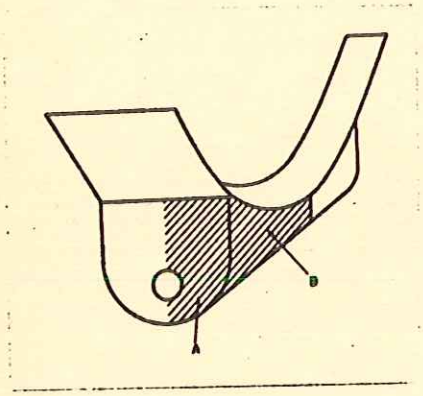


Fig. 13

Total amount of heat loss is four times as much as heat loss from the part shaded in the left sketch.

Result of Calculation:

Q_A : Heat loss from Part A

$= 1.28$

Q_B : Heat loss from Part B

$= 6.65$

Total amount of heat loss is

$4\ (Q_A + Q_B)$

$= 4\ (1.28 + 6.65)$

$= 31.7$ kcal/hr

2.3 Conclusion

Heat Loss from Pivot Pin	37.2 x 2 =	74.4 kcal/hr
Heat Loss from Cover	31.7	31.7
Total		106.1

Total Heat Loss from Support Shoe 106.1 x 2 = 212.2 kcal/hr

3 Heat Calculation - Model B

Purpose of calculation : to obtain the heat loss figures from a support structure.

3.1 Heat Loss from Pivot Pin

When the heat resistance at each portion is determined as shown in Fig. 14, the heat flow can be converted into the diagram of Fig.15.

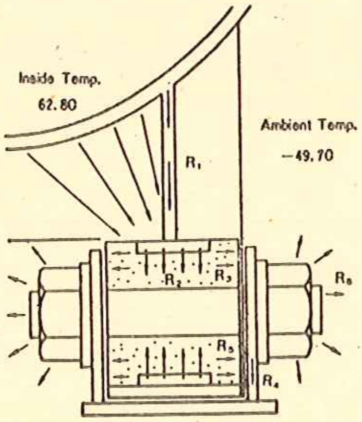


Fig. 14

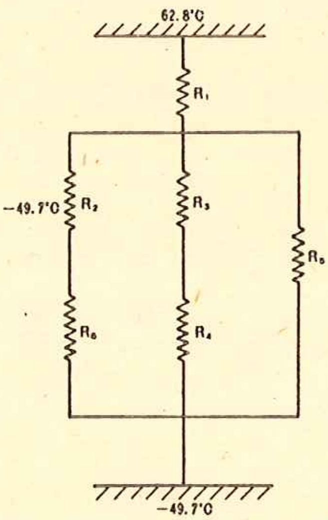


Fig. 15

The heat flow calculated from Fig. 15 is larger in value than the actual heat flow due to the following reasons.

i) As to the heat flow from the bottom of a rib to a sleeve, it is assumed that all the heat is transferred through the rib, because the heat loss through polyurethane foam insulation is negligible.

ii) A temperature of the sleeve is assumed to be unfiorm at any part, though actually there is temperature difference between the upper and the lower parts of sleeve; therefore, quantity of heat transferred through the bushing to the pivot pin varies at the

the upper and the lower parts of the pin.

iii) The heat flows through the sleeve longitudinally and circumferentially. It is assumed that the heat flows longitudinally not only through the sleeve but also through 1/3 of bushing in contact with the sleeve.

iv) Thermal distribution in the inside of the pivot pin and nut is not uniform due to the heat flow. But inside heat resistance is negligible, since it is much smaller than the surface heat resistance dependent on the surface area and surface thermal conductivity.

Computations based on the assumptions i) thro iv) above may be expected to serve the present purpose with reasonable accuracy. These assumptions are such that the computed heat losses may be somewhat higher, but never be lower, than actual heat losses.

The heat loss is calculated by the use of the formula:

$$Q = \frac{(Q_o - Q_r)}{R} \qquad \ldots (1)$$

Where,

Q = Heat loss from pivot pin (kcal/hr)

Q_o = Inside temperature 62.8 (°c)

Q_r = Ambient temperature -49.7 (°c)

R = Total of R_1 thro' R_6

a) R_1 (Heat Resistance of Rib)

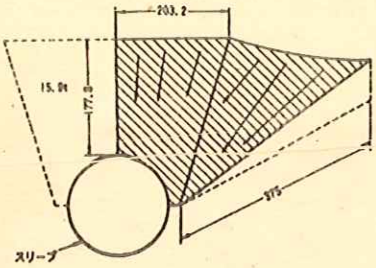


Fig. 16

The value of heat resistance to be calculated for the part shaded in Fig.16.

R is the half of the value obtained above.

S (cross section of heat flow route) is 0.00426 (m).

t (average distance of heat flow route) is 0.289 (m).

λ (thermal conductivity) is 45 (kcal/m·hr·°c)

$$\text{Then, } R_1 = \frac{1}{S\lambda} \times \frac{1}{2} = \frac{0.289}{0.00426 \times 45} \times \frac{1}{2} = 0.753$$

b) R_2 (Heat Resistance of Bushing against Heat Flow to Pivot Pin)

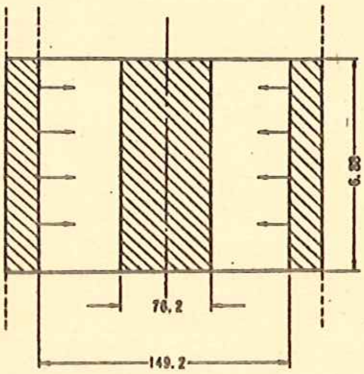


Fig. 17

$$R_2 = \frac{1}{2\pi\lambda L} \log \frac{d_2}{d_1}$$

$$= \frac{1}{2 \times 3.14 \times 0.248 \times 0.0889} \times \log \frac{0.1492}{0.0762} = 4.853$$

λ = Thermal conductivity of bushing 0.248 (kcal/m·hr·c)

L = Width of sleeve 0.0889 (m)

d_2 = Inside diameter of outer sleeve 0.1492 (m)

d_1 = Outside diameter of inner sleeve 0.0762 (m)

c) R_3 (Heat Resistance of Bushing against Outward Heat Flow)

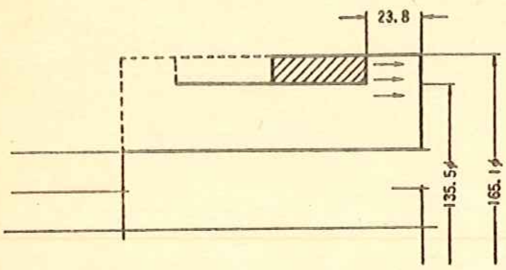


Fig. 18

$$S = \frac{\pi}{4} (0.1651 - 0.1355) \times \frac{1}{2}$$

$$= 0.00349$$

$$t = 0.0238$$

The heat flows in both right and left directions; therefore, R_3 is taken as a half of $t/s\lambda$.

$$R_3 = \frac{0.0238}{0.00249 \times 0.248} \times \frac{1}{2} = 13.749$$

d) R_4 (Heat Resistance against Heat Flow from Metal Plate to Support)

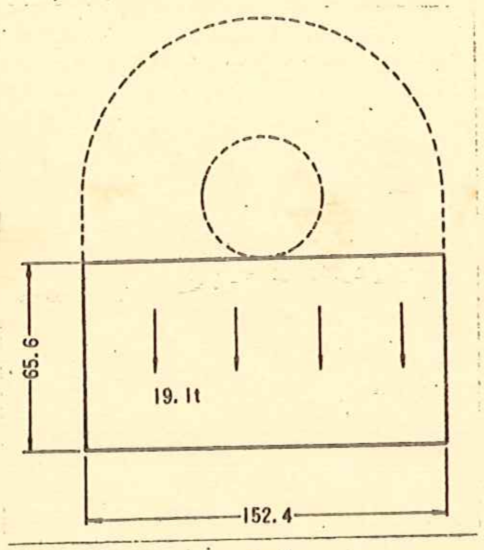


Fig. 19

$S = 0.0191 \times 0.1524 = 0.00290$

$t = 0.0656$

$$R_4 = \frac{0.0656}{0.00290 \times 45} \times \frac{1}{2}$$

$$= 0.251$$

e) R_5 (equal to R_3)

f) R_6 (Heat Resistance on the Surfaces)

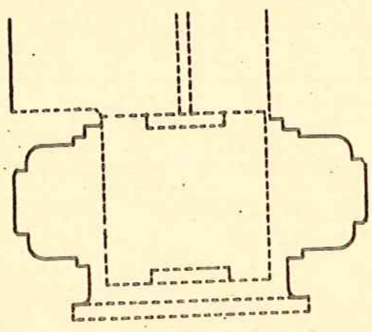


Fig. 20

S (total surface area as drawn with solid lines in Fig. 20) is 0.179.

$$R_6 = \frac{1}{S\alpha}$$

Where, α= surface thermal conductance (kcal/m^2·hr·°c)

Then, $$R_6 = \frac{1}{0.179 \times 23.4}$$

$$= 0.239$$

Put the results of a) thro' f) in Fig. 15, then Fig. 21 is obtained.

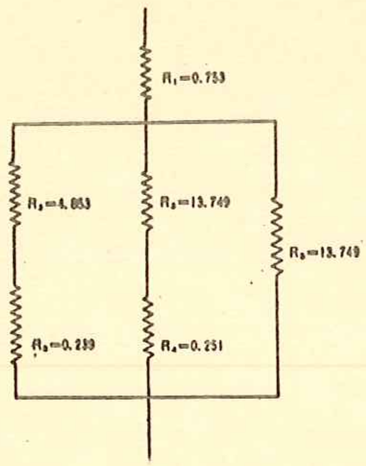


Fig. 21

$R_{26} = R_2 + R_6$

$= 4.853 + 0.239 = 5.092$

$R_{34} = R_3 + R_4$

$= 13.749 + 0.251 = 14.000$

Combine three parallel resistance circuits (R_{26}, R_{34} and R_5)

$$\frac{1}{R_{23456}} = \frac{1}{R_{26}} + \frac{1}{R_{34}} + \frac{1}{R_5} = \frac{1}{5.092} + \frac{1}{14.0} + \frac{1}{13.749}$$

$\therefore \quad R_{23456} = 2.936$

Add R_1 to R above, then the total heat resistance (R) is obtained.

$R = 2.936 + 0.753 = \underline{3.689}$

Calculate the heat loss from pivot pin with formula (1).

$$Q = \frac{(62.8 - (-49.7))}{3.689} = 30.5 \text{ kcal/hr}$$

3.2 Heat Loss From Basket (Q)

Q is four times as much as heat loss value from the shaded part in Fig. 22.

$$Q = \frac{S(Q_o - Q_r)}{\frac{t}{\lambda} + \frac{1}{\alpha}}$$

S = Surface area (m^2)

Q_o = Inside temperature (°c)

Qr = Ambient temperature (°c)

t = Thickness of polyurethane insulation (m)

λ = Thermal conductivity of polyurethane (kcal/m.hr.°c)

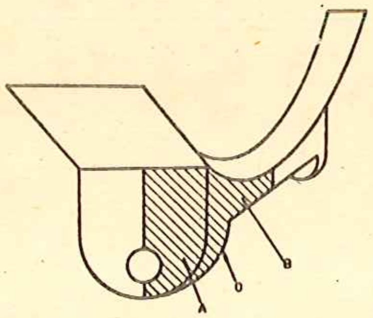


Fig. 22

Because of unequal thicknesses of covers, heat loss is calculated respectively at three portions, A, B and C as shown in Fig. 22.

Results of calculation:

$Q_A = 2.10$ $\quad$ $Q_B = 2.64$ $\quad$ $Q_C = 2.01$

Then, toal heat loss $(Q) = 4\ (Q_A + Q_B + Q_C)$

$= \underline{27.0\ \text{kcal/hr}}$

3.3 Conclusion

Heat loss from Pivot Pin	30.5 x 2 = 61.0 kcal/hr
Heat loss from Cover	27.0
Total	88.0

Total Heat Loss From Support Shoe : 88.0 x 2 = 176.0 kcal/hr

4 Influence of Heat Loss From Support On The Entire Heat Loss

Comparative analytical studies will be made to see how much the heat loss of the entire system is influenced by heat loss from the support.

4.1 Purpose of calculation: to evaluate a ratio of heat loss from support to heat loss from the entire system.

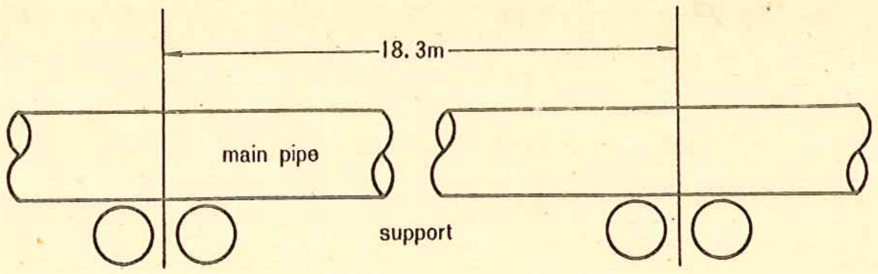


Fig. 23

If it is assumed that heat loss from main pipe is within the allowable heat loss specified, heat loss per unit length is

132.3 kcal/m·hr (or 160 BTU/ft·hr).

Heat loss from the pipe between supports (Q_1) is

132.3 x 18.3 = 2,420 kcal/hr.

Let heat loss from the support be Q_2.

Ratio of Q to the total heat loss is

$$\frac{Q_2}{Q_1 + Q_2} \times 100\ (\%).$$

Then, Model A : $\frac{212.2 \times 100}{2{,}420 + 212.2}$

$= 8.1\%$

Model B : $\frac{176.0 \times 100}{2{,}420 + 176.0}$

$= 6.8\%$

5. Test Program for Analysis of Heat Loss From Support Structure

5.1 Purpose

Herein dealt with is the test which is conducted in order to obtain the amount of heat loss from support shoe insulated with "pin and cover insulation system."

The test solely aims at obtaining directly the total amount of heat loss with the aid of electric apparatus and, therefore, is not intended for obtaining accurate values of thermal conductivity of components (steel, bushing, jacket, insulation, etc.) at low temperature of -57.5°F.

5.2 Test Equipment

Refer to Fig. 24 (Side View of Test Equipment).

A : Cold chamber insulated with rigid polyurethane foam insulation

B : Steel structures, including

a : saddle clamp

b : pivot pin

c : support plate

d : support lag

C : Electric heater, consisting of

D : Main heater

E : Main guard heater

F : Insulation

J : Molded plastic casing insulation

The cold chamber (A) is equipped with two sets of fans (G) to insure appropriate air circulation. The air is cooled and kept at - 57.5°F by the use of liquid nytrogen (H) and temperature regulator.

The thermal output of Main Heater is measured electrically with Voltmeter and Ammeter. The Guard Heater is designed to prevent the transfer of heat from Main Heater outward, so that all of the heat from Main Heater flows into the cold chamber.

Sub-Guard Heater (I) also is arranged for the same purpose as necessary.

Also refer to Fig. 25 (Front View of Test Equipment) and Fig. 26 (Arrangement of Test Equipment).

5.3 Test Procedure

a. Temperature Control

Cold chamber is prechilled with dry ice down to the ambient temperature in arctic area, i.e. minus 57.5°F, and the temperature is kept at a constant level by the automatic liquid nitrogen feeder. Air in the chamber is stirred by two fans to keep even temperature.

In order to simulate the on-site operation, the steel surface is electrically heated with Main Heater by adjusting the power supply to the assumed oil temperature of 145°F. Guard Heater, having the insulation layer between it and the Main Heater, collaterally adjusts the power supply in order to keep the both surfaces of the insulation layer at the same temperature.

That is because the total heat of the Main Heater should be conducted to the Support Shoe. Regarding the End Heater, the same principle is applied to prevent the end effect. When the whole system comes to the thermally constant level, the following measurements are made.

b. Measurement

b-1 Heat Loss

Heat loss from the support structure is calculated from the following equations by the power input to the main heater:

$Q = P \times 0.860 - Qj = E \times I \times 0.860$ (kcal/hr·unit)

P : Power input to Main Heater (watt)

E and I : Voltage and ampere to Main Heater respectively

Qj : Heat loss from Molded Plastic Casing b-2 Temperature Measurement

Thermo-couples are attached to the main positions of the Support Shoe Assembly to measure the temperatures of each position under the given conditions in order to prepare for the unexpected trouble in the future.

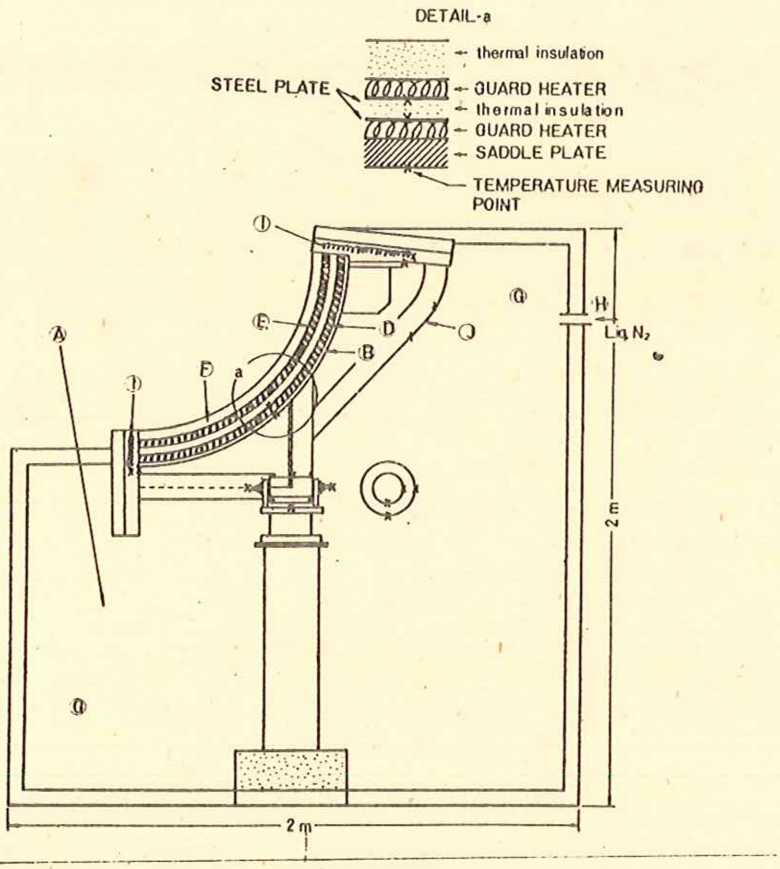


Fig. 24 Side View of Test Equipment

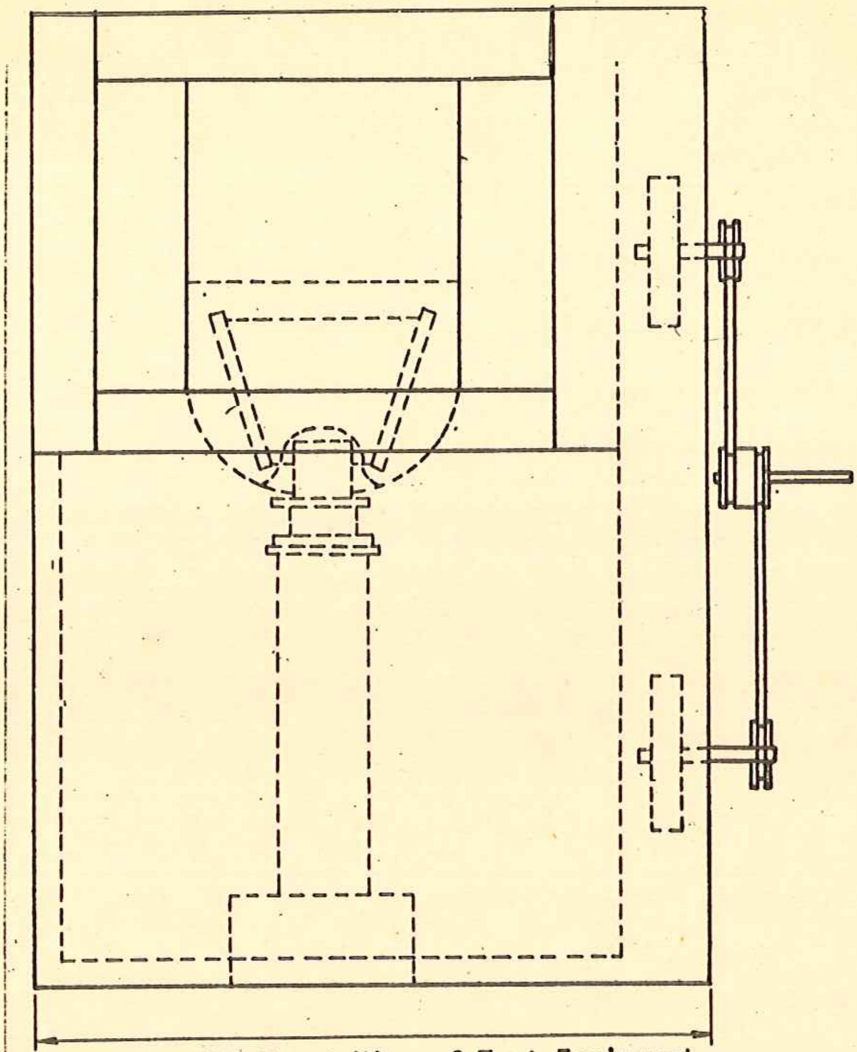


Fig. 25 Front View of Test Equipment

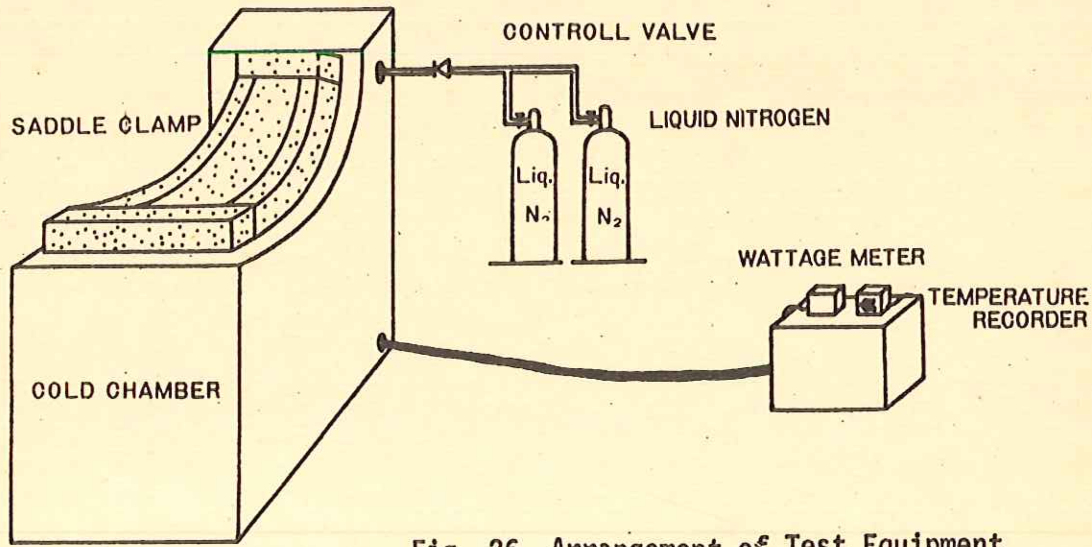


Fig. 26 Arrangement of Test Equipment

6 Conclusion

A series of experimental studies is still being conducted at the time of this writing; therefore, this paper cannot include a complete report on the experimental results. So far, however, the experiments have indicated the results fairly identical with those arrived at by the analysis. The authors wish to have a chance on an adequate occasion to augment the present paper by describing in some detail the experiments and the data derived from them as they firmly believe that the analysis method as introduced here is highly effective for planning of hot oil pipelines.

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