Optimization of Cooled Shields in Insulations

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ABSTRACT

A relatively simple method has been developed to optimize the location, temperature, and heat dissipation rate of each cooled shield inside an insulation layer. The method is based on the minimization of the entropy production rate which is proportional to the heat leak across the insulation. The results show that the maximum number of shields to be used in most practical applications is three. However, cooled shields are useful only at low values of the overall, cold wall to hot wall absolute temperature ratio. The performance of the insulation system is relatively insensitive to deviations from the optimum values of temperature and location of the cooling shields.

Design curves are presented for rapid estimates of the locations and temperatures of cooling shields in various types of insulations, and an equation is given for calculating the cooling loads for the shields.
NOMENCLATURE

A  Area of heat flow, m²

Cₚ  Specific heat of the boiloff vapor, kJ/kg·K

D  Functional defined by Eq. (14)

F  Functional defined by Eq. (13)

hfg  Latent heat of vaporization of the boiloff liquid, kJ/kg

k  Thermal conductivity, W/m·K; with subscripts, coefficients in Eq. (1)

L  Overall thickness of insulation, m*

m,n  Exponents in conductivity function, Eq. (1)

P  Tₛ/Tₖ, temperature ratio

q  Heat flow rate, W

R  Tₖ/Tₕ, overall temperature ratio

s  Dimensionless entropy production rate defined by Eq. (5)

S  Entropy production rate, W/K

t  Thickness between walls with single shield between, m*

T  Absolute temperature, K

x  Distance from cold wall, m*

x'  Distance from cold wall in a multi-shield configuration, m*

X  x/t, dimensionless distance*

X'  x'/L, dimensionless distance*

γ  Defined by Eq. (8)

Subscripts

C  Cold wall

H  Hot wall

i  i-th shield

min  Minimum

opt  Optimum

S  Shield

*For systems with single shield L = t, x = x', X = X'.
INTRODUCTION

The search for the ultimate, energy efficient insulation system has led in the past few years to a fascinating rediscovery and application of some fundamental concepts of thermodynamics: specifically, the second law and the use of entropy production rates and availability (or exergy) for design optimization purposes. The classical approach has been to minimize the heat flow between surfaces at different temperatures.

The concept of a single vapor-cooled shield in an insulation has been treated theoretically as far back as 1959 in Scott's classic textbook on cryogenics [1] and designs employing them were described not much later [2]. Paivanas, et al., obtained a patent [3] and later reported on the use of uniformly spaced multiple shields which were cooled by the boil-off from the insulated dewar [4]. Eyssa and Okasha [5] considered only radiative heat exchange between shields and minimized the total refrigeration power required. Hilal, et al., [6,7] used a similar minimization of refrigeration power as the design basis. Related works were reported by Bejan, et al., [8-11].

Recently, Bejan [12] proposed a new point of view, based on the second law of thermodynamics, which considers thermal insulations as dissipators of useful mechanical power (i.e. the availability or exergy) or, alternately, as generators of irreversibility or entropy. Thus, in this method, optimization of an insulation corresponds to minimization of either the entropy production rate or the irreversibility, or the decrease of availability. Various applications of this concept to insulation systems have been documented subsequently [13,14].

Our work grew out of an examination of Cunnington's paper [13] who utilized a numerical technique to find optimum temperatures at given locations for one and two shields for a thermal conductivity function of the form
Although several equations seemed to be incorrectly printed we have found two of the design curves to be essentially correct. Thus, our purpose was:

1. To develop a simple optimization technique;
2. To generalize the results to a broader class of insulations; and
3. To develop simple design methods for cooled shields.

The essentials of this report were already published [15].
ANALYSIS

We accept the previously developed concept that to optimize an insulation system is equivalent to minimizing the entropy production rate. In addition, we assume one-dimensional heat flow and that the heat capacity of the boil-off gas is adequate to do the cooling for all shields and does not impose a restriction on the optimization. In contrast to Rejan [9,11] who has developed a constrained optimization based on the heat capacity of the boiloff we employ the argument that in all practical systems the boil-off is generated by cooling of some equipment in addition to the heat leakage across the insulation.

Parallel heat paths, e.g. supports, have not been considered. However, each path can be optimized separately using its own thermal conductivity function. Then a design decision has to be made whether the two structures should be independently cooled at their respective optimum conditions.

We examine the general situation of an insulation where equivalent thermal conductivity, $k$, can be expressed as a two-term function of the absolute temperature

$$k = k_1 T^m + k_2 T^n$$

(1)

where, typically, the first term represents actual conduction with $m = 1$ and the second term represents radiation with $n \geq 3$. In the following, $m$ and $n$ can be any value except -1.

The heat flow across a layer of insulation can be expressed in terms of Fourier's law

$$q \, dx = Ak \, dT$$

(2)
Substituting $k$ from Eq. (1) and integrating across a layer from one end at 1, to the other at 2, yields

$$q = \frac{A}{x_2 - x_1} \left[ \frac{k_1}{n+1} (T_2^{m+1} - T_1^{m+1}) + \frac{k_2}{n+1} (T_2^{n+1} - T_1^{n+1}) \right]. \quad (3)$$

Now consider the insulation with a cooled shield at $T_S$ located at $x$ between a hot surface at $T_H$ and a cold one at $T_C$, separated by the insulation thickness, $t$, as shown in Fig. 1a. The entropy production rate for the insulation can be determined from the heat flows and temperatures as follows

$$S = -\frac{q_H}{T_H} + \frac{q_C}{T_C} + \frac{q_S}{T_S} \quad (4)$$

where $q_S = q_H - q_C$.

The heat flow terms can be expressed in the form of Eq. (3) and the resulting expression can be non-dimensionalized using the following terms

$$s \equiv \frac{St}{Ak_H} \quad \text{where} \quad k_H = k \text{ at } T_H, \quad (5)$$

$$P \equiv \frac{T_S}{T_C}, \quad (6)$$

$$R \equiv \frac{T_C}{T_H}, \quad (7)$$

$$\gamma \equiv \frac{k_2(n+1)}{k_1(n+1)} \frac{T_{n-m}}{T_H}, \quad (8)$$

and

$$x \equiv \frac{t}{t}. \quad (9)$$
The resulting equation is

\[ s(m + 1)(1 + \gamma \frac{n + 1}{m + 1}) \]

\[ = \frac{1}{1 - \chi} \left\{ [(PR)^m + 1 - (PR)^m - 1 + (PR)^{-1}] + \gamma[(PR)^{n+1} - (PR)^n - 1 + (PR)^{-1}] + \frac{1}{X} \{ R^m[p^{m+1} - p^{m} - 1 + p^{-1}] + \gamma r^n[p^{n+1} - p^{n} - 1 + p^{-1}] \} \right\} \]

(10)

Since \( R \), the overall temperature ratio, is generally known, \( s \) is a function of \( P \) and \( X \), and its extreme value can be found by differentiating it with respect to each variable separately and setting the results equal to zero. This procedure yields two equations to be solved simultaneously: \( \frac{\partial s}{\partial P} = 0 \) and \( \frac{\partial s}{\partial X} = 0 \). Because of the regular form of the expressions, one of the final two equations contains only a single unknown as follows:

\[ \frac{R^m F(m, P) + \gamma R^n F(n, P)}{[R^{m-1} D(m, P) + \gamma R^{n-1} D(n, P)]^2} = \frac{F(m, PR) + \gamma F(n, PR)}{[D(m, PR) + \gamma D(n, PR)]^2} \]

(11)

\[ \frac{X}{1 - \chi} = -\frac{R^{m-1} D(m, P) + \gamma R^{n-1} D(n, P)}{D(m, PR) + \gamma D(n, PR)} \]

(12)

where the following functionals were used:
Thus, to find the optimum temperature and location for a shield, Eq. (11) can be solved for \( P \), and then \( X \) can be calculated from Eq. (12). The heat to be removed by the shield, \( q_s = q_H - q_C \), can be found, as before, from Eq. (3). In dimensionless form the equation becomes

\[
\frac{q_s}{Ak_H} = \frac{(m+1)(1 + \gamma^{n+1})}{(1 - (PR)^{m+1}) + \gamma[1 - (PR)^{n+1}]}
\]

or

\[
(1 - X)(PR)^{m+1} - R^{m+1} + \gamma[(PR)^{n+1} - R^{n+1}]
\]

(15)

For multiple shields \( \tau_i \) represents the distance between the two surfaces surrounding the \( i \)-th shield on either side, \( T_{H,i} \) and \( T_{C,i} \) are the temperatures of these two surfaces, \( X_i = x_i/\tau_i \) is the location of the shield relative to \( \tau_i \), and \( x_i' \) is the location of the shield relative to the cold wall as shown in Fig. 1b. To determine the optimum temperatures and locations for multiple shields, first we assumed a temperature for the first shield next to the cold wall, then we used Eqs. (11) and (12) to find the temperature and location of the second shield. This process was repeated for the rest of the shields and the hot wall. Thus, each shield was optimized consecutively with respect to the two surfaces on either side. With given values of the overall temperature ratio, \( R \), and of the number of shields, the process requires iterative solution.
To put the results into proper perspective, the entropy production rates can be compared to the thermodynamically minimum rate obtainable through spatially continuous cooling. According to Bejan [12], this rate is

\[ S_{\text{min}} = \frac{A}{t} \left[ \int_{T_C}^{T_H} (k) \frac{1}{T^2} \right] \left[ \frac{1}{T} \right] dt \].

(16)

This expression was evaluated analytically for the single-term functions of \( k \), i.e. for \( \gamma = 0 \), and numerically otherwise.
RESULTS AND DISCUSSION

The first set of curves, Figs. 2 through 9, show the relative entropy production rates for various thermal conductivity functions and for up to four optimally cooled shields as functions of the overall temperature ratio \( R \equiv T_C/T_H \). The curves show that the entropy production rate increases with decreasing values of the temperature ratio, \( R \), and with increasing values of the exponent, \( m \) and \( n \). Adding shields, of course, reduces the entropy production rate; but for most of the practical temperature range, say \( 0.01 < R < 0.4 \), only three shields contribute to significant decreases and adding a fourth shield can be considered unnecessary. No shields are useful at high values of \( R \); but this "high" range is strongly dependent on the exponent of the temperature. The curves developed with \( k = k_1 T^{0.6} \) for one and two shields were very close to those given by Cunnington [13], converted appropriately.

Study of the results of two-term conductivities reveals that the curves fall between those obtained for each of the two terms alone. If \( \gamma \) is small the first term, \( T^m \), dominates; whereas if \( \gamma \) is large (>10), the second term, \( T^n \), controls. Thus, general conclusions can be drawn from examining the results of the single-term conductivities.

The second set of curves, Figs. 10 through 31, show the optimum temperature ratios, \( T_S/T_H \), and optimum locations, \( x'/L \), of cooled shields as functions of the overall temperature ratio, \( T_C/T_H \), for various thermal conductivity functions and with different number of cooled shields.

Figures 10 and 11 show the optimum single shield temperature ratios, \( PR = T_S/T_H \), and locations, \( X = x/L \), for five conductivity functions. Both of these functions generally decrease with decreasing \( R \). The other figures in this set show shield temperatures and locations for systems with up to three
shields and for both single-term and two-term conductivities. The results are strongly non-linear. For example, for $k_1 T^3$ and $R = 0.01$, the optimum temperature ratios for three shields are about 0.09, 0.3, and 0.6 and the optimum locations are about 0.05, 0.2, and 0.5. As is to be expected, our unconstrained optimization yields a somewhat better performance per shield than Bejan's [9,11] constrained method.

The sensitivities of the entropy production rates to deviations from the optimum values of PR and X are demonstrated in the last set of curves, Figs. 32 through 35, for single shields. The sensitivity increases with the value of the exponents, m and n, but the curves are relatively flat near the minima. A ±20 percent change from optimum, for example, has negligible effect. Thus, the system is relatively tolerant of deviations from the optimum design conditions.

Calculations with two different conductivities on the two sides of a cooled shield show that using the better insulator on both sides always yields the optimum condition. However, if for some reason two types of insulations have to be used, then the better insulator should be placed on the warm side of the shield.
REFERENCES


Figure 1 Schematic of the Nomenclature for (a) Single and (b) Multiple Shields
Curve Set 1: Figures 2 through 9

The effect of optimally cooled shields on

the entropy production rate for various thermal conductivities.
\[ k = k_1 T_0^{0.6} \]

No. of Shields

\[ \frac{T_{\text{cold}}}{T_{\text{hot}}} \]

Figure 3
Figure 6

The diagram shows the relationship between the ratio of cold to hot temperatures ($T_{cold}/T_{hot}$) and the ratio of production rate to minimum production rate ($S/S_{min}$). The equation $k = k_1 T^{3.0}$ is given, and the graph represents the number of shields with different line styles corresponding to 0, 1, 2, 3, and 4 shields.
$k = k_1 T + k_2 T^{3.0}$  \( \gamma = 2.0 \)

No. of Shields

$S/S_{\text{min}}$

$T_{\text{cold}}/T_{\text{hot}}$

Figure 8
Figure 9

$k = k_1 T + k_2 T^3$, $\gamma = 5.0$

No. of Shields

$S/S$

$T_{cold}/T_{hot}$
Curve Set 2: Figures 10 through 31

Optimal shield temperatures and locations for various thermal conductivity functions with different number of shields.
\[ \left[ \frac{T_{\text{shield}}}{T_{\text{hot}}} \right]_{\text{opt}} \]

\[ \frac{T_{\text{cold}}}{T_{\text{hot}}} \]

No. of Shields = 1

- \( k = k_1 \)
- \( k = k_1 T^{0.6} \)
- \( k = k_1 T \)
- \( k = k_1 T^{2.0} \)
- \( k = k_1 T^{3.0} \)

Figure 10
No. of Shields = 1

- $k = k_1$
- $k = k_1 T^{0.6}$
- $k = k_1 T$
- $k = k_1 T^{2.0}$
- $k = k_1 T^{3.0}$

$\left[ \frac{X}{L} \right]_{opt}$

$T_{cold} / T_{hot}$

Figure 11
\[ k = k_1 T^{0.6} \]

No. of Shields = 2

- - - - - SHIELD 1
- - - - - SHIELD 2

Figure 12
\[ k = k_1^T 0.6 \]

No. of Shields = 3

\[ \frac{T_{\text{cold}}}{T_{\text{hot}}} \]
\[ k = k_1 T \]

No. of Shields = 3

SHIELD 1
SHIELD 2
SHIELD 3

\[ \frac{T_{\text{cold}}}{T_{\text{hot}}} \]
$k = k_1 T$

No. of Shields = 3

- SHIELD 1
- SHIELD 2
- SHIELD 3

$\frac{[X/L]_{opt}}{T_{cold}/T_{hot}}$

Figure 17
\[ k = k_1 T^{3.0} \]

No. of Shields = 2

---

**Figure 18**
$k = K_1 T^{3.0}$

No. of Shields = 2

Figure 19
$k = k_1 T^{3.0}$

No. of Shields = 3

Figure 20
\[ k = k_1 T^{3.0} \]

No. of Shields = 3

- **SHIELD 1**
- **SHIELD 2**
- **SHIELD 3**

Figure 21
No. of Shields = 1

- \( k = k_1 T + k_2 T^{3.0} \) for \( \gamma = 0.5 \)
- \( k = k_1 T + k_2 T^{3.0} \) for \( \gamma = 2.0 \)
- \( k = k_1 T + k_2 T^{3.0} \) for \( \gamma = 5.0 \)

Figure 22
$k = k_1 T + k_2 T^{3.0}$, $\gamma = 0.5$

No. of Shields = 2

---

Figure 24
$k = k_1 T + k_2 T^{3.0}$  \(\gamma = 0.5\)  No. of Shields = 2

---

**Figure 25**

---

$\left[ \frac{X}{L} \right]_{opt}$

---

$\frac{T_{cold}}{T_{hot}}$

---

[Graph showing the relationship between $\left[ \frac{X}{L} \right]_{opt}$ and $\frac{T_{cold}}{T_{hot}}$ for different shields.]
\[ k = k_1 T + k_2 T^{3.0} \quad \gamma = 0.5 \]

No. of Shields = 3

---

Figure 26
$k = k_1 + k_2 T^{3.0}$

$\gamma = 0.5$

No. of Shields = 3

Figure 27

$T_{\text{cold}}/T_{\text{hot}}$

$\frac{\gamma}{X}$
\[ k = k_1 T + k_2 T^{3.0} \]
\[ \gamma = 2.0 \]
\[ \text{No. of Shields} = 2 \]

Figure 28
The diagram illustrates the relationship between $X'/L_{opt}$ and $T_{cold}/T_{hot}$ for different values of $k = k_1 T + k_2 T^{3.0}$, with a parameter $\gamma = 2.0$. It compares two shield types, labeled as SHIELD 1 and SHIELD 2. The graph shows that as $T_{cold}/T_{hot}$ increases, $X'/L_{opt}$ also increases for both shield types. The figure is labeled as Figure 29.
Figure 30

\[ k = k_1 T + k_2 T^{3.0} \quad \gamma = 2.0 \]

No. of Shields = 3

- SHIELD 1
- SHIELD 2
- SHIELD 3
Curve Set 3: Figures 32 through 35

System sensitivity to deviations from the optimum shield temperatures and locations for two overall temperature ratios with one cooled shield
\[
\frac{T_{\text{cold}}}{T_{\text{hot}}} = 0.006
\]

- \( k = k_1 \)
- \( k = k_1 T \)
- \( k = k_1 T^{3.0} \)

**Figure 32**
$T_{\text{cold}}/T_{\text{hot}} = 0.006$

- $k = k_1$
- $k = k_1 T$
- $k = k_1 T^{3.0}$

Figure 33
$T_{\text{cold}} / T_{\text{hot}} = 0.060$

- $k = k_1$
- $k = k_1 T$
- $k = k_1 T^{3.0}$

Figure 34
\[ \frac{T_{\text{cold}}}{T_{\text{hot}}} = 0.060 \]

\[ k = k_1 \frac{T}{T_{3.0}} \]

\[ k = k_1 \]

Figure 35
APPENDIX

COMPUTER PROGRAMS
SEPARS and SHIELD

These two programs are essentially identical, but SEPARS is written in PASCAL whereas SHIELD is in BASIC.

To allow for consecutive calculations of different systems, the program always recycles to the starting point. Consequently, the first input requested is either a 1, if a calculation is to be performed, or a 0, if no more work is to be done.

Next the program requests input of the insulation's characteristics, specifically, the two exponents of the temperatures in the two-term conductivity function, the maximum number of cooled shields (<10) to evaluate, the value of $\gamma$, and the temperature ratio of the first shield to the cold wall, $P(1) = T_{S1}/T_C$. The program calculates and presents the characteristics of all optimal systems of cooled shields from one shield to the maximum number specified in the input.

The flow chart and a program sample follows.
TO PERFORM COMPUTATION, ENTER 1. OTHERWISE, ENTER 0. READ PFC

IS PFC = 1?

NO

YES

ENTER INSULATION CHARACTERISTICS, NUMBER OF SHIELDS AND P(I)

I = 1

IM1 = I - 1
IM2 = I - 2

SOLVE R(I) ITERATIVELY

CALCULATE S(I), X(I)

IS I > 1?

NO

YES

L2(I) = (1.0 - X(I-1)) / X(I)

IS I > 2?

NO

YES

IS I > 3?

NO

YES

FOUR OR MORE SHIELDS ARRANGEMENT
ASSIGN B AND L4(I)

ONE SHIELD ARRANGEMENT
ASSIGN L3(I), TCH(I), TSH(I), L4(I) AND XPL(I)

TWO SHIELDS ARRANGEMENT
ASSIGN L4(2) AND TCH(2)

THREE SHIELDS ARRANGEMENT
ASSIGN L4(3) AND TCH(3)

FIVE OR MORE SHIELDS ARRANGEMENT
ASSIGN B AND L4(I)

W

A

A

B
TSH(I+1) = 1.0
T2(I) = TCH(I)

IS I = 1?

YES

J = 2

T2(J) = TSH(J-1)
J = J + 1

IS J = 1?

NO

YES

ASSIGN L3(I+1) AND S(I+1)
J = 1

CALCULATE Q(J), SISH(J)

OUTPUT THE HEAT REMOVAL RATE AND ENTROPY PRODUCTION RATE AT EACH SHIELD ALONG WITH OPTIMUM LOCATION AND OPTIMUM TEMPERATURE FOR THE SHIELDS' ARRANGEMENT

J = J + 1

IS J = 1?

NO

YES

CALCULATE QHOT, QCOLD AND SCOLD

CALCULATE STOTAL(I)

CALCULATE SMIN(I), STOTMIN(I), SMAX(I), SMAIN(I)

IS I = NS?

NO

YES

P(I+1) = 1.0 / P1

2
OUTPUT TCH(I), QCOLD, QHOT, SCOLD, SMIN(I), SMA(I), STOTAL(I), SMA(I) AND STOTMIN(I)

I = I + 1

IS I > NS?

YES

TO PERFORM COMPUTATION, ENTER 1. OTHERWISE, ENTER 0. READ PFC

IS PFC = 1?

YES

END SEPARS

NO
**Program Shields (Input/Output.JMK)**

This Pascal program was developed to optimize the location, temperature and heat dissipation rate of each cooled shield inside an insulation layer. The thermal conductivity of the insulation has the general form:

\[
\text{\textit{K}} = \text{\textit{K}}\text{\textit{a}}(\text{\textit{T}}\text{\textit{m}}) + \text{\textit{K}}\text{\textit{b}}(\text{\textit{T}}\text{\textit{m}}) + \text{\textit{K}}\text{\textit{c}}(\text{\textit{T}}\text{\textit{m}})
\]

The method is based on the minimization of the entropy production rate which is proportional to the heat leak across the insulation.

This program allows for the optimization of shields inside an insulation layer, considering their location, temperature, and heat dissipation rate. It utilizes the general form of the thermal conductivity of the insulation material and minimizes the entropy production rate to optimize the system.
PROCEDURE INPUT.

BEGIN (* INPUT OF DATA HEADER *)

ED (* INPUT OF DATA HEADER *)

PROCEDURE PFCH.

BEGIN (* PFCH *)

END (* PFCH *)

PROCEDURE SINGLESPACE.

BEGIN (* SINGLE SPACE IN OUTPUT *)

END (* SINGLE SPACE IN OUTPUT *)

FUNCTION PW(XXE REAL) REAL.

VAR A REAL.

BEGIN (* COMPUTE XX**E *)

END (* COMPUTE XX**E *)

FUNCTION D(XX REAL) REAL.

BEGIN (* FUNCTIONAL D *)

END (* FUNCTIONAL D *)
FUNCTION SIMPSON(TC,H REAL); REAL.

TYPE
   ARR=ARRAY(1:10) OF REAL;

VAR
   C T
   DELT
   N
   K L
   INTEGER.

BEGIN
   (* COMPUTE MINIMUM ENTROPY PRODUCTION RATE USING SIMPSON'S NUMERICAL INTEGRATION SCHEME *)

   DELT = TCH/100.0;
   FOR I = 1 TO 10 DO
   BEGIN
      K = (I-1)*DELTA;
      YM = ((DELTA*(K+1))/2)+DELTA/2;
      YC = ((DELTA*(K+1))/2)+DELTA/2;
      IF K MOD 2 = 0 THEN
         X = K/2;
      ELSE
         X = K/2;
      END;
      H = ((DELTA/2)+DELTA/2);
   END;
   (* main program body *)

   BEGIN
   PR.

   READ(FC).
   WHILE FPC<1 DO
   BEGIN

   (* this block is used to input the insulation thermal conductivity number *)

   (* OF SHIELDS AND 1ST SHIELD / COLD WALL TEMPERATURE RATIO *)

   INPUT
   READEN
   READ(N,M,NE,CAMA,PI).
   SINGLESPACE.
   IF CAMA<0 G THEN
      WRITELN(' THERMAL CONDUCTIVITY OF THE INSULATION IS X = E1*T**.M.3.1')
   ELSE
      BEGIN
      WRITELN(' THERMAL CONDUCTIVITY OF THE INSULATION IS X = E1*T**.M.3.1')
      END;
   END;
   SINGLESPACE.
   SINGLESPACE.
   BEGIN
   NP = M+1.
   NP1 = M+1.
   FOR I = 1 TO M DO
   BEGIN
   IM = I-1.
   IM2 = I-2.
   R(I) = 0.00001.
   CC = 0.1.
   DD = 0.9.
   COUNT = 0.
   END;
(* THIS BLOCK CALCULATES R13 ITERATIVELY *)

REPEAT

R1 = -P33(R13).
R1 = -P33(R13) + P33(R13) + GAMA*P33(R13).

V1 = SQR(P33(R13), M-1)*P33(R13) + GAMA*P33(R13).
V2 = SQR(P33(R13), M-1)*P33(R13) + GAMA*P33(R13).
V3 = SQR(P33(R13), M-1)*P33(R13) + GAMA*P33(R13).

G = (V1/2) + V3.
G = -G/D.
IF G > 0 THEN GOTO 100.
IF G < 0 THEN GOTO 200.

CC = (-1) + CC.
DC = -DD.
100 R13 = R13 + CC.

IF (R13) OR (R13) THEN

BEGIN

R13 = R13 + CC.
CC = 0 + CC.
END.

100 COUNT + COUNT + 1.
UNTIL (G1 = 0) OR (ABS(1) = 0).

(* IN THIS BLOCK VARIABLES ARE ASSIGNED FOR DIFFERENT SHIELD CONFIGURATIONS *)

IF (;) THEN

BEGIN

L33 = (0 - R13)/R13.
IF (;) THEN

BEGIN

R = 0.
L43 = 0.
FOR J = 2 TO IM1 DO

BEGIN

B = B + 1.
L43 = L43 + B.
END.

L43 = L43 + 1.
L0 = 0.
FOR J = 2 TO IM1 DO

BEGIN

B = B + 1.
L43 = L43 + B.
END.

L43 = L43 + 1.
L0 = 0.
TCH = TCH + 1.
FOR J = 2 TO IM1 DO TCH = TCH + P33.
END.

ELSE

BEGIN

L33 = 0.
R = (1 - X13)/(1 - X13).
TCH = TCH + P33.
END.

ELSE

BEGIN

L33 = R33/P33.
TCH = TCH + P33.
END.

L33 = L33.
XPL = X13/L33.
FOR J = 2 TO 1 DO

BEGIN

LJ3 = L33/J13.
XPL = X13/L33.
END.

TSH = TSH + P33.
FOR J = 2 TO 1 DO TSH = TSH + P33.
END.

ELSE


BEGIN
L(1) = 1.0.
TCM(1) = 1.0.
TSH(1) = TCH(1)*P(1).
L(8) = 1.0.
EPL(I) = 0.
END.
TSH(I+1) = 0.
TCM(I) = TCH(I).

SINGLESPACE.
WRITE*: NUMBER OF SHIELDS = ',I 2).
WRITE*: NUMBER OF ITERATIONS = ',COUNT 1).
SINGLESPACE.
WRITE*: HEAT REMOVAL RATE
WRITE*: ENTROPY PRODUCTION RATE
WRITE*: OPTIMUM LOCATION
WRITE*: OPTIMUM TEMPERATURE.
SINGLESPACE.
IF (I) THEN
FOR J = 1 TO I DO T2(J) = TSH(J-1).
L(j-1) = L(j).
J-1 = 0.

(*) IN THIS BLOCK DIMENSIONLESS HEAT REMOVAL AND ENTROPY PRODUCTION RATES (*)
(*) ARE CALCULATED FOR EACH SHIELD (*)

FOR J = 1 TO I DO
BEGIN
Z = (PWR(TCM(J-1),MP1)-PWR(TCM(J),MP1))*L(J-1)/L(J)*((PWR(TSH(J),MP1)-PWR(TCH(J),MP1))*L(J-1)/L(J)).
Z = (PWR(TCM(J-1),MP1)-PWR(TCM(J),MP1))*L(J-1)/L(J)*((PWR(TSH(J),MP1)-PWR(TCH(J),MP1))*L(J-1)/L(J)).
SISH(J) = G(I) = TSH(J).
WRITE*: "SHIELD " J I : 5.0(JI) 9 5. ' 11.SISH(JI) 9 5. ' 9.EPL(J) 9 5. ' 5.TSH(JI) 9 5.
END.

(*) FINALLY OTHER QUANTITIES OF INTEREST ARE CALCULATED IN THIS BLOCK *)

SINGLESPACE.
QHOT = (G(I) - PVR(TCM(J),MP1))/GAMA - MP1 + PWR(TCH(J),MP1)) + L(J-1)/L(J) - PVR(TSH(J),MP1)) + L(J-1)/L(J).
QCOLD = (PWR(TCM(J),MP1) - PWR(TCH(J),MP1)) + GAMA - MP1 + PWR(TCH(J),MP1)) + L(J-1)/L(J).
SMA1 = 'S(J) = MPSON(TCH(J)).
STOTM = STOTM + SMA1.
SMA1 = 'S(J) = MPSON(TCH(J)).
TOTAL = TOTAL + SMA1.

IF (IONS THEN F(I+1) = 0/2.
SINGLESPACE.
WRITE*: COLD WALL / HOT WALL TEMPERATURE RATIO = 'TCH(JI) 14.4).
WRITE*: HEAT IN AT COLD WALL = 'TCH(JI) 14.4).
WRITE*: ENTROPY PRODUCTION RATE AT COLD WALL = 'TCH(JI) 14.4).
WRITE*: MINIMUM ENTROPY PRODUCTION RATE = 'TCH(JI) 14.4).
WRITE*: TOTAL ENTROPY PROD RATE WITH 'I.3.' SHIELDS = 'TCH(JI) 14.4).
WRITE*: MAXIMUM / MINIMUM ENTROPY PRODUCTION RATIO = 'TCH(JI) 14.4).

SINGLESPACE.
SINGLESPACE.
SINGLESPACE.
SINGLESPACE.

END.
READ
READ
READ
PFCH.
READ
READ
END

**
TO PERFORM COMPUTATION, ENTER 1. OTHERWISE, ENTER 0.

ENTER ----> M N NS GAMA P[1] -----

WHERE:  M ------ 1ST. POWER IN THE THERMAL CONDUCTIVITY EQUATION
        N ------ 2ND. POWER IN THE THERMAL CONDUCTIVITY EQUATION
        NS ------ NUMBER OF SHIELDS
        GAMA -- #0 IF USING ONE TERM THERMAL CONDUCTIVITY EQUATION
                >0 IF USING TWO TERM THERMAL CONDUCTIVITY EQUATION
        P[1] -- 1ST. SHIELD / COLD WALL TEMPERATURE RATIO ALWAYS > 1

1.0  3.0  1  2.5  15.0

THERMAL CONDUCTIVITY OF THE INSULATION IS K = K1*T**1.0 + K2*T**3.0

[2*K2*(M+1)]/[K1*(M+1)]*THOT**(N-M) = 2.50

NUMBER OF SHIELDS = 1
NUMBER OF ITERATIONS = 35

HEAT REMOVAL RATE | ENTROPY PRODUCTION RATE | OPTIMUM LOCATION | OPTIMUM TEMPERATURE
SHIELD 1 | 0.43837 | 1.85659 | 0.36744 | 0.23611

COLD WALL / HOT WALL TEMPERATURE RATIO = 0.015741
HEAT OUT AT COLD WALL = 0.014350
HEAT IN AT HOT WALL = 0.452719
ENTROPY PRODUCTION RATE AT COLD WALL = 0.911631
ENTROPY PRODUCTION RATE AT HOT WALL = -0.452719
MINIMUM ENTROPY PRODUCTION RATE = 1.000503
MAXIMUM ENTROPY PRODUCTION RATE = 18.236148
TOTAL ENTROPY PRODUCTION RATE WITH 1 SHIELDS = 2.315503
MAXIMUM / MINIMUM ENTROPY PRODUCTION RATIO = 18.226962
TOTAL / MINIMUM ENTROPY PRODUCTION RATIO = 2.314340

TO PERFORM COMPUTATION, ENTER 1. OTHERWISE, ENTER 0.

ENTER ----> M N NS GAMA P[1] -----

WHERE:  M ------ 1ST. POWER IN THE THERMAL CONDUCTIVITY EQUATION
        N ------ 2ND. POWER IN THE THERMAL CONDUCTIVITY EQUATION
        NS ------ NUMBER OF SHIELDS
        GAMA -- #0 IF USING ONE TERM THERMAL CONDUCTIVITY EQUATION
                >0 IF USING TWO TERM THERMAL CONDUCTIVITY EQUATION
        P[1] -- 1ST. SHIELD / COLD WALL TEMPERATURE RATIO ALWAYS > 1

1.0  0.0  2  0.0  25.0

THERMAL CONDUCTIVITY OF THE INSULATION IS K = K1*T**1.0

NUMBER OF SHIELDS = 1
NUMBER OF ITERATIONS = 23
## Heat Removal Rate and Entropy Production Rate

<table>
<thead>
<tr>
<th>Shield</th>
<th>Heat Removal Rate</th>
<th>Entropy Production Rate</th>
<th>Optimum Location</th>
<th>Optimum Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shield 1</td>
<td>0.75466</td>
<td>7.03151</td>
<td>0.35870</td>
<td>0.10732</td>
</tr>
</tbody>
</table>

- **Cold Wall / Hot Wall Temperature Ratio**: 0.004293
- **Heat Out at Cold Wall**: 0.016030
- **Heat In at Hot Wall**: 0.770687
- **Entropy Production Rate at Cold Wall**: 3.734070
- **Entropy Production Rate at Hot Wall**: -0.770687
- **Minimum Entropy Production Rate**: 3.504633
- **Maximum Entropy Production Rate**: 115.966533
- **Total Entropy Prod. Rate with 1 Shields**: 9.994893

## Number of Shields = 2

**Number of Iterations**: 36

<table>
<thead>
<tr>
<th>Shield</th>
<th>Heat Removal Rate</th>
<th>Entropy Production Rate</th>
<th>Optimum Location</th>
<th>Optimum Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shield 1</td>
<td>0.05470</td>
<td>2.71297</td>
<td>0.17465</td>
<td>0.02016</td>
</tr>
<tr>
<td>Shield 2</td>
<td>0.884-1</td>
<td>4.70678</td>
<td>0.48690</td>
<td>0.18786</td>
</tr>
</tbody>
</table>

- **Cold Wall / Hot Wall Temperature Ratio**: 0.000806
- **Heat Out at Cold Wall**: 0.001162
- **Heat In at Hot Wall**: 0.940073
- **Entropy Production Rate at Cold Wall**: 1.440716
- **Entropy Production Rate at Hot Wall**: -0.940073
- **Minimum Entropy Production Rate**: 3.921467
- **Maximum Entropy Production Rate**: 619.477774
- **Total Entropy Prod. Rate with 2 Shields**: 7.920388

**Maximum / Minimum Entropy Production Ratio**: 157.970919

**Total / Minimum Entropy Production Ratio**: 2.019751

To perform computation, enter 1. Otherwise, enter 0.

? 0

0.175 CPU secs, 124158 CM used.
PROGRAM SHIELD

1 00010 REM THIS IS A "BASIC" PROGRAM TO CALCULATE OPTIMUM TEMPERATURES.
2 00020 REM LOCATIONS, AND COOLING LOADS FOR COOLED SHIELDS IN A CRYOCENIC
3 00030 REM: INSULATION SYSTEM WHOSE THERMAL CONDUCTIVITY FOLLOWS THE RELATION
4 00040 REM 1/0=C*1/T-H0+ C1/T-H1
5 00050 REM MODIFIED IN LATE NOV. 1982.
6 00060 REM
7 00060 REM DEFINITION OF SYMBOLS USED
8 00070 REM
9 00010 REM COLD-SIDE WALL TEMPERATURE T0
10 00020 REM WARM-SIDE WALL TEMPERATURE T1
11 00030 REM SPACING BETWEEN SHIELDS AT I-1 AND I-1 L(I-1)
12 00040 REM OVERALL THICKNESS OF INSULATION L
13 00050 REM LOCAL SPACING RATIO: L(I-1)/LI(L-1) L2(I)
14 00060 REM OVERALL SPACING RATIO: L/L(I) L4(I)
15 00070 REM DISTANCE FROM COLD WALL TO L(I)
16 00080 REM I-TH SHIELD TEMPERATURE T(I)
17 00090 REM I-TH SHIELD POSITION RATIO X(I)
18 00100 REM I-TH SHIELD TEMPERATURE RATIO P(I) (ALWAYS 1)
19 00110 REM I-TH COLD-WARM TEMPERATURE RATIO R(I) (ALWAYS 1)
20 00120 REM I-TH DIMENSIONLESS ENTROPY PRODUCTION RATE S(I)
21 00130 REM I-TH DIMENSIONLESS HEAT REMOVAL RATE Q(I)
22 00140 REM TOTAL DIMENSIONLESS ENTROPY PRODUCTION RATE S2(I)
23 00150 REM MINIMUM ENTROPY PRODUCTION RATE S0(I)
24 00160 REM ENTROPY PRODUCTION RATE WITHOUT SHIELDS S(I)
25 00170 REM NUMBER OF SHIELDS M (M OR 10)
26 00180 REM
27 00190 DIM X(M),T(M),Q(M)
28 00200 PRINT "INPUT : I IF MORE WORK IS TO BE DONE, 0 IF FINISHED"
29 00210 INPUT A
30 00220 PRINT "INPUT NO.M,NO.M,CAMMA & P(I)"
31 00230 INPUT NO,NO,M,CAMMA,P(I)
32 00240 DEF FNF(Y1) = NO-MO-(Y1-1-MO)-1/(Y1-)
33 00250 DEF FNF(Y2) = MO-MO-(Y2-1-MO)-1/(Y2-)
34 00260 DEF FNC1R1) = R1*(NO-MO-(Y1-1-MO)-1/(Y1-)
35 00270 DEF FNC1R2) = R2*(MO-MO-(Y2-1-MO)-1/(Y2-)
36 00280 DEF FND1(PO) = G0+FGNP(PO)
37 00290 DEF FND2(PO) = G0+FGNP(PO-1)
38 00300 PRINT "EXPERIMENT NO.X,NO.M,CAMMA.G,NO.U";
OF POOR QUALITY
140 01283 FOR K=2 TO 180
150 01284 IF K/I=INT(K/I) THEN 01287
151 01285 IF=K=2*INT(K)
152 01286 GO TO 01286
153 01287 IF=K=K+1
154 01288 NEXT K
155 01290 S(K)=(D/3*M/[1]/(1+G0*M)/M)
156 01291 S(K)=S2(K)/S0(K)
157 01292 S(K)=S1(K)*B0*(1+G0*M)(((1+G0*M)/M)/(1+G0*M)/M)
158 01293 S(K)=S2(K)/S0(K)
159 01294 IF K>THEN 01270
160 01295 IF=K=1
161 01296 IF=K=K+1
162 01297 PRINT
163 01298 PRINT "PQ=P(0), Rn=R(0), E*E(0), E1=E(1), S=S(0)
164 01299 PRINT
165 01300 PRINT "COLD WALL/HOT WALL TEMPERATURE RATIO, TO/TRY.B0(1)
166 01301 PRINT "HEAT OUT AT COLD WALL=60, HEAT IN AT WARM WALL=80
167 01302 PRINT "ENTROPY PRODUCTION RATE AT COLD WALL=S8
168 01303 PRINT "ENTROPY PRODUCTION RATE AT WARM WALL=S9
169 01304 PRINT "MINIMUM ENTROPY PRODUCTION RATE. S0=S0(1)
170 01305 PRINT "ENTROPY PRODUCTION RATE FOR".SHIELDS. S1=S1(I)
171 01306 PRINT "MAXIMUM ENTROPY PRODUCTION RATE. S9=S9(1)
172 01307 PRINT "ENTROPY PRODUCTION RATE RATIOS. S0=S0/50 AND S4=S4/50'
173 01308 PRINT
174 01309 NEXT I
175 01310 IF=K=10370
176 01311 IAC
177 "EOP"
This program solves the original, complete, constrained optimization equations developed in Ref. [9] without the simplifying assumption suggested there which eliminated the dimensionless parameter, \( h_{fg}/C_p T_H \). Only single-term thermal conductivity functions were considered in this analysis.

This program also recycles to the starting point. Consequently, the first input is either a 1, if a calculation is to be performed, or a 0, if no more work is to be done.

Next the program requests input of the insulation's characteristics, specifically, the exponent of temperature in the thermal conductivity function, the number of cooled shields, the dimensionless parameter \( h_{fg}/C_p T_H \) for the boiloff from the insulated container, and \( R = T_C/T_H \).

The output specifies the optimal characteristics of the given number of shields with the constraint that the cooling capacity is limited to the boiloff of the liquid due only to the heat leak through the insulation itself.

The flow chart and a program sample follows.
BEGIN NEWRAF

TO PERFORM COMPUTATION, ENTER 1. OTHERWISE, ENTER 0. READ PFC.

IS PFC = 1 ?

NO

YES

ENTER INSULATION CHARACTERISTICS, NUMBER OF SHIELDS, HF / (CP * THOT) AND TCH

ASSIGN TSHG(I)'S WHICH ARE THE INITIAL GUESSES FOR TSH(I)'S

COUNT = 0
EPS = 1 OE-10

COUNT = COUNT + 1

ASSIGN ELEMENTS OF THE TRIDIAGONAL MATRIX A(I), B(I), C(I) AND ALSO D(I) BASED ON TSHG(I)'S AND OTHER DATA

SOLVE THE SYSTEM OF EQUATIONS FOR THE TSH(I)'S USING THE TRIDIAGONAL MATRIX SOLVER

I = 1

TSH(I) = TSHG(I) - TSH(I)
I = I + 1

IS I > NS ?

NO

YES

CALCULATE DIFFMAX, THE MAXIMUM OF |TSH(I) - TSHG(I)| I = 1, ..., NS

IS DIFFMAX > EPS ?

NO

YES
TO PERFORM COMPUTATION: ENTER 1. OTHERWISE: ENTER 0.

END NEWRF.

IS PFC = 1

YES

A

NO

B

IS I

YES

CALCULATE QHOT, QCOLD, SCOLD, SMIN AND STOTAL

I = I + 1

NO

CALCULATE QI(I), SISH(I)

OUTPUT THE HEAT REMOval RATE AND ENTROPY PRODUCTION RATE AT EACH SHIELD ALONG WITH OPTIMUM LOCATION AND OPTIMUM TEMPERATURE FOR THE SHIELDS' ARRANGEMENT.

CALCULATE QHOT, QCOLD, SCOLD, SMIN AND STOTAL

SOLVE FOR SPR(I, I)

ASSIGN MRF(I, I)'S

C

YES

D

IS I

NOT

1

I = 1

NO

TS(H)(I) = TSH(I)
THIS PASCAL PROGRAM WAS DEVELOPED TO OPTIMIZE THE LOCATION, TEMPERATURE AND HEAT DISSIPATION RATE OF EACH COOLED SHIELD INSIDE AN INSULATION LAYER. THE OBJECTIVE HAS BEEN TO SOLVE THE SET OF NONLINEAR EQUATIONS OBTAINED BY BEJAN, A. "DISCRETE COOLING OF LOW HEAT LEAK SUPPORTS TO 4.2 K." CRYOCENICS, VOL 15, 1975, PP 290-292. SOLUTION IS BASED ON THE NEWTON-RAPHSON TECHNIQUE DISCUSSED BY STOECKER, W. F., DESIGN OF THERMAL SYSTEMS, 2ND EDITION, SECTION 4-11, PP 117-119, MCGRAW-HILL BOOK CO., NY, 1980.

PARAMETER DEFINED IN PROCEDURE INPUT:

OUT. FILE TO BE USED IF DESIRED.

THE SIZE OF ARRAYS DETERMINES THE MAXIMUM NUMBER OF SHIELDS.

THE SIZE OF ARRAYS IS N5-1.

THE SIZE OF ARRAYS SHOULD BE TWICE THE NUMBER OF SHIELDS.

LOWER-DIAGONAL ELEMENTS OF THE TRIDIAGONAL MATRIX.

DIAGONAL ELEMENTS OF THE TRIDIAGONAL MATRIX.

UPPER-DIAGONAL ELEMENTS OF THE TRIDIAGONAL MATRIX.

RIGHT-HAND SIDE OF THE SET OF EQUATIONS DURING ITERATIONS.

1-TH DIMENSIONLESS HEAT REMOVAL RATE.

DIMENSIONLESS HEAT TRANSFER BETWEEN SHIELDS.

DIMENSIONLESS ENTROPY PRODUCTION RATE FOR 1-TH LATER.

MAXIMUM DIMENSIONLESS ENTROPY PRODUCTION RATE.

MINIMUM DIMENSIONLESS ENTROPY PRODUCTION RATE.

SHAI / SHIN.

TOTAL DIMENSIONLESS ENTROPY PRODUCTION RATE.

STOTAL / SHIN.

I-TH DIMENSIONLESS ENTROPY PRODUCTION RATE.

I-TH SHEILD / HOT WALL TEMPERATURE RATIO, ALWAYS (1).

GUESSED I-TH SHEILD / HOT WALL TEMPERATURE RATIO, ALWAYS (1).

DUMMY VARIABLES.

SPACING BETWEEN NEIGHBORING SHIELDS / INSULATION THICKNESS.

DISTANCE FROM COLD WALL / INSULATION THICKNESS.

DISTANCE BETWEEN COOLED SHIELDS.

OUTPUT FILE TO BE USED IF DESIRED.

PARAMETER DEFINED IN PROCEDURE INPUT.
**ORIGINAL PAGE 71**

**OF POOR QUALITY**

```
PROCEDURE INPUT.
BEGIN
  (* INPUT OF DATA HEADING *)
  WRITELN.
  WRITELN:
  ENTER ------ M NS BETA TCH ------.
  WRITELN:
  WHERE M ----- POWER IN THE THERMAL CONDUCTIVITY EQUATION.
  NS ----- NUMBER OF SHIELDS.
  BETA ----- HFC / (CP*THOT).
  TCH ----- COLD WALL / HOT WALL TEMPERATURE RATIO, ALWAYS (1).
  WRITELN:
  END:
  (* INPUT OF DATA HEADING *)

PROCEDURE PCH.
BEGIN
  (* PCH *)
  WRITELN:
  TO PERFORM COMPUTATION. ENTER 1. OTHERWISE. ENTER 0.
  WRITELN:
  END:
  (* PCH *)

PROCEDURE SINGLESPACE.
BEGIN
  (* SINGLE SPACE IN OUTPUT *)
  WRITELN(" ")
  ENCS
  (* SINGLE SPACE IN OUTPUT *)

FUNCTION PWRE(X,E REAL) REAL.
VAR
  A
BEGIN
  A = EXP(X).
  PWRE = A*EXP(E).
END:
  (* COMPUTE E**E *)

FUNCTION MAXOF2(N01,N02 REAL) REAL.
BEGIN
  (* DETERMINES THE LARGEST OF THE TWO GIVEN NUMBERS *)
  IF N01>N02 THEN
    MAXOF2 = N01
  ELSE
    MAXOF2 = N02
END:
  (* DETERMINES THE LARGEST OF THE TWO GIVEN NUMBERS *)
```
FUNCTION MINOF1(NO1,NO2 REAL REAL:
BEGIN (* DETERMINES THE SMALLEST OF THE TWO GIVEN NUMBERS *)
  IF NO1 < NO2 THEN
    MINOF1 :=NO1
  ELSE
    MINOF1 :=NO2
END. (* DETERMINES THE SMALLEST OF THE TWO GIVEN NUMBERS *)

(* MAIN PROGRAM BODY *)
BEGIN
  PCH:
  READ:
  READ:SPEC:
  WHILE PEG=1 DO
  BEGIN
    (* THIS BLOCK IS USED TO INPUT THE INSULATION THERMAL CONDUCTIVITY, NUMBER *)
    (* OF SHIELDES. HFC/(CP*THOT) AND COLD WALL / HOT WALL TEMPERATURE RATIO *)
    INPUT
    READ:
    READ:MNS BETA TCH)
    SINGLESPACE.
    WRITE:
      THERMAL CONDUCTIVITY OF THE INSULATION IS K = E1*T**M3 1),
      HFC / (CP*THOT) = BETA 5).
    WRITE:
    SINGLESPACE
    SINGLESPACE.
    MF :=-1.0.
    MM :=-1.0.
    (* INITIAL GUESSED VALUES FOR TSH:11: S ARE ENTERED *)
    DELTATC :=( E1-TCH)/(MNS: B).
    FOR J := TO MS DO TSH:11: :=J*DELTATC* TCH.
    (* VARIABLE USED TO CHECK CONVERGENCE CRITERION IS SET AND THE ITERATIVE PROCEDURE *)
    (* NEWTON-RAPHSON METHOD IS STARTED *)
    IFS := 0: 10.
    COUNT :=0.
    IT1 :=0.
    REPEAT
      COUNT :=COUNT +1.
      FOR I := TO MS DO
      BEGIN
        = TSH:11:.
        IF MS :=1 THEN
          IF (I) THEN
            BEGIN
              GIM :=TSH:11:-1.
              GIP :=TSH:11:+1.
              END.
            ELSE
              BEGIN
                GIM :=TSH:11:-1.
                GIP := I.
                END.
            ELSE
              BEGIN
                GIM :=TCH.
                GIP :=TSH:11:+1.
                END.
            END.
      END.
END.
(* ELEMENTS OF THE TRIDIAGONAL MATRIX ARE COMPUTED *)

A(I):=FWR(G(1,MP)-FWR(GI,M)-FWR(GI,M)*FWR(TCH-BETA)).
B(I):=FWR(GI,M)+FWR(GI,M)*FWR(BETA-TCH-GI)*FWR(BETA-TCH).)
C(I):=FWR(GI,M)*FWR(BETA-TCH-CI).
D(I):=FWR(GI,M)-FWR(GI,M)*FWR(BETA-TCH-GI)*FWR(BETA-TCH).)
E(I):=FWR(GI,M)*FWR(BETA-TCH-GI).

END.

(* THE TRIDIAGONAL MATRIX SOLVER IS SHOWN IN THIS BLOCK *)
(* SEE WESTLAKE, J. R., A HANDBOOK OF NUMERICAL MATRIX *)
(* SOLUTION AND SOLUTION OF LINEAR EQUATIONS, SECTION *)
(* I., §7, PP 34-35, JOHN WILEY & SONS, INC., NY, 1968 *)

IF E(I)=0 THEN GOTO 100.
BOLD :=BOLD/E(I).
GOLD :=GOLD/E(I).
WORKING :=GOLD.
DMAX :=ABS(BOLD).
DMIN :=ABS(GOLD).
BOLD :=BOLD - DMIN/DMAX.
GOLD :=GOLD - DMIN/DMAX.
WORKING :=GOLD.
END.

FOR I = 1 TO NS DO
BEGIN
D(I) := 1 + ABS(TSHC(TSHC(TSHC(TSHC))).
IF D(I)=0 THEN GOTO 100.
DMAX :=MAX(DMAM,ABS(D(I)).
DMIN :=MIN(DMAM,ABS(D(I)).
BOLD :=BOLD - DMIN/DMAX.
GOLD :=GOLD - DMIN/DMAX.
WORKING :=GOLD.
END.

FOR I = 1 TO NS DO TSHC:=TSHC(TSHC(TSHC(TSHC))).
FOR I = 1 TO NS DO TSHC:=TSHC(TSHC(TSHC(TSHC))).

(* CONVERGENCE IS CHECKED. IF THE CRITERION IS SATISFIED, THE ITERATION IS *)
(* TERMINATED. OTHERWISE THE NEWLY CALCULATED TSHC'S ARE USED AS NEW *)
(* GUESSES FOR ANOTHER ROUND OF ITERATION *)

DIFFMAX :=ABS(TSHC(TSHC(TSHC(TSHC))).
FOR I = 1 TO NS DO
BEGIN
DIFF :=ABS(TSHC(TSHC(TSHC(TSHC))).
DIFFMAX :=MAX(DIFF,DIFFMAX).
END.
IF DIFFMAX < EPS THEN
ITERIN :=ITERIN + 1.
ELSE
FOR I = 1 TO NS DO TSHC:=TSHC(TSHC(TSHC(TSHC))).
UNTIL ITERIN.

(* IN THE BLOCK QUANTITIES USED IN DETERMINING THE SHIELDS' SPACINGS ARE COMPUTED *)

FOR I = 1 TO NS DO
BEGIN
T(I) := TSHC(TSHC(TSHC(TSHC))).
IF NS(I) THEN
IF (I) THEN
IF (I) THEN
TIP := TSHC(TSHC(TSHC(TSHC))).
ELSE
TIP := TSHC(TSHC(TSHC(TSHC))).
ELSE
TIP := TSHC(TSHC(TSHC(TSHC))).
BEGIN

DEN = 0;
FOR I = 1 TO NS DO DEN = DEN + X[I]*2NS-1 + 1 + 1; 0;
NSP = NSP + 1;

(* FINALLY. SPACINGS BETWEEN SHIELDS AND OTHER QUANTITIES OF INTEREST ARE CALCULATED *)

X[1] = 0/DEN;
X[P1][1] = X[I];
TOTAL = TOTAL;
FOR I = 2 TO NSP DO BEGIN
    X[I] = X[1-I]+X[I-1];
    IF (NSP) THEN X[I] = X[I]+I[I];
    TOTAL = TOTAL + I[I];
END.

IF (ABS(TOTAL-0.0) 1.0E-5) THEN GOTO 100.
If (NSP-1) THEN GOTO 100.

BEGIN
    NSP = NSP;
    QOLD = QOLD;
    QOLD = QOLD + 1;
    TOTAL = 10COLD + QOLD;
    FOR I = 1 TO NSP = TOTAL = xX[I];
    IF Y = 1/0 0 THEN
        SPAT = QOLD((0-PW(TCH, MP/2.0)))/(MP/2.0))
    ELSE
        SPAT = QOLD((0-PW(TCH, MP/2.0)))/(MP/2.0))
    STOTMIN = STOTMIN;
    SMAX = SMAX/SMIN;
    SMS = SMS;
    BEGIN
        COLD WALL / HOT WALL TEMPERATURE RATIO = TCH 14.40;
        HEAT OUT AT COLD WALL = QOLD 14.40;
        HEAT IN AT HOT WALL = QOLD 14.40;
        ENTROPY PRODUCTION RATE AT COLD WALL = SCOLD 14.40;
        ENTROPY PRODUCTION RATE AT HOT WALL = -QOLD 14.40;
        MINIMUM ENTROPY PRODUCTION RATE = SMIN 14.40;
        MAXIMUM ENTROPY PRODUCTION RATE = SMAX 14.40;
        TOTAL ENTROPY PRODUCTION RATE WITH 'NS 2' SHIELDS = STOTAL 14.40;
        MAXIMUM / MINIMUM ENTROPY PRODUCTION RATIO = SMAX 14.40;
        TOTAL / MINIMUM ENTROPY PRODUCTION RATIO = STOTMIN 14.40;

        IF (DIM=6 0) OR (DIM=1=0 0) THEN
            CHECK THE ASSEMBLY OF COEFFICIENTS TO BE USED IN TRIDIAGONAL MATRIX
            CHECK THE TRIDIAGONAL MATRIX SOLVER

        END.

        IF (ABS(TOTAL-1.0) 1.0E-5) THEN
            STOTAL IS NOT EQUAL TO 1.0
            CONVERGENCE IS NOT CORRECT

        END.

        END.

        END.

        END.

        END.

        END.

        END.

        END.

        END.
00 PFCH.
01 HEADIN.
02 HEAD(PFC)
03 END
04 ENC
05 /EDP.
To perform computation, enter 1. Otherwise, enter 0.

? 1

Enter: ——— M NS BETA TCH ———

Where:

M ——— Power in the thermal conductivity equation
NS ——— Number of shields
BETA — MFG / (CP*THOT)
MFG ——— Heat of vaporization [J/kg]
CP ——— Specific heat at constant pressure [J/kg K]
THOT ——— Hot wall temperature [K]
TCH ——— Cold wall / hot wall temperature ratio, always 1

? 1.0 3 0.0145 0.001

Thermal conductivity of the insulation is k = k₁ * t**1.0
MFG / (CP*THOT) = 0.01450

Number of shields = 3
Number of iterations = 9

<table>
<thead>
<tr>
<th>Heat removal rate</th>
<th>Entropy production rate</th>
<th>Optimum location</th>
<th>Optimum temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shield 1</td>
<td>0.10438</td>
<td>1.56143</td>
<td>0.09719</td>
</tr>
<tr>
<td>Shield 2</td>
<td>0.25983</td>
<td>1.12595</td>
<td>0.28870</td>
</tr>
<tr>
<td>Shield 3</td>
<td>0.47781</td>
<td>0.89782</td>
<td>0.58568</td>
</tr>
</tbody>
</table>

Cold wall / hot wall temperature ratio = 0.001000
Heat out at cold wall = 0.022985
Heat in at hot wall = 0.864998
Entropy production rate at cold wall = 22.984544
Entropy production rate at hot wall = -0.864998
Minimum entropy production rate = 3.751018
Maximum entropy production rate = 499.499501
Total entropy prod. rate with 3 shields = 25.704743
Maximum / minimum entropy production ratio = 133.163725
Total / minimum entropy production ratio = 6.852735

To perform computation, enter 1. Otherwise, enter 0.

? 1

Enter: ——— M NS BETA TCH ———

Where:

M ——— Power in the thermal conductivity equation
NS ——— Number of shields
BETA — MFG / (CP*THOT)
MFG ——— Heat of vaporization [J/kg]
CP ——— Specific heat at constant pressure [J/kg K]
THOT ——— Hot wall temperature [K]
TCH ——— Cold wall / hot wall temperature ratio, always 1

? 1.0 2 0.0134 0.000806
THERMAL CONDUCTIVITY OF THE INSULATION IS K = K1 = 1.0  
MFG / (CP*THOT) = 0.01540

NUMBER OF SHIELDS = 2  
NUMBER OF ITERATIONS = 8

<table>
<thead>
<tr>
<th></th>
<th>HEAT REMOVAL RATE</th>
<th>ENTROPY PRODUCTION RATE</th>
<th>OPTIMUM LOCATION</th>
<th>OPTIMUM TEMPERATURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHIELD 1</td>
<td>0.19732</td>
<td>1.97595</td>
<td>0.16252</td>
<td>0.09986</td>
</tr>
<tr>
<td>SHIELD 2</td>
<td>0.39037</td>
<td>1.48999</td>
<td>0.48495</td>
<td>0.39623</td>
</tr>
</tbody>
</table>

COLD WALL / HOT WALL TEMPERATURE RATIO = 0.000806  
HEAT OUT AT COLD WALL = 0.030677  
HEAT IN AT HOT WALL = 0.018366  
ENTROPY PRODUCTION RATE AT COLD WALL = 38.061092  
ENTROPY PRODUCTION RATE AT HOT WALL = -0.818366  
MINIMUM ENTROPY PRODUCTION RATE = 3.776103  
MAXIMUM ENTROPY PRODUCTION RATE = 519.846992  
TOTAL ENTROPY PROD. RATE WITH 2 SHIELDS = 40.708665  
MAXIMUM / MINIMUM ENTROPY PRODUCTION RATIO = 164.149921  
TOTAL / MINIMUM ENTROPY PRODUCTION RATIO = 10.780603

TO PERFORM COMPUTATION, ENTER 1. OTHERWISE, ENTER 0.

? 0
0.072 CP SECS, 11471B CM USED.
/ BYE:

3KMUFTC COSTS: 255.028 SRUS AT $0.0059 = $1.50
DESINS

This program optimizes the characteristics of a single cooled shield with different insulations on the two sides. Only one-term thermal conductivity functions are considered.

This program also recycles to the starting point; thus the first input is 1, if a calculation is to be performed, or 0 if no more work is to be done.

Next inputs are the characteristics of the two insulations, specifically, the exponents of temperature in the thermal conductivity functions on the hot and cold sides of the shield, a coefficient ratio ALFA (defined in the program), the shield to cold wall temperature ratio, $P = T_S/T_C$, and the hot wall temperature, $T_H$.

The output specifies the optimal characteristics of the cooled shield as well as other, related information.

The flow diagram and a program sample follows.
BEGIN DESIGNS

TO PERFORM COMPUTATION, ENTER 1. OTHERWISE, ENTER 0. READ PFC

IS PFC = 1? NO

YES

ENTER THE TWO INSULATIONS' CHARACTERISTICS, P AND HOT WALL TEMPERATURE

SOLVE TCH ITERATIVELY

CALCULATE X1 AND X

CALCULATE QHOT, QCOLD, SCOLD, STOTAL, SISH, SMIN1, SMIN2, SMAX1 AND SMAX2

OUTPUT TCH, TSH, QCOLD, QHOT, SCOLD, SISH, SMIN1, SMIN2, STOTAL, SMAX1 AND SMAX2

TO PERFORM COMPUTATION, ENTER 1. OTHERWISE, ENTER 0. READ PFC

IS PFC = 1? YES

NO

END DESIGNS
PROGRAM DiffCond(input, output, sem);

(* THIS PASCAL PROGRAM WAS DEVELOPED TO OPTIMIZE THE *)
(* LOCATION, TEMPERATURE AND HEAT DISSIPATION RATE *)
(* FOR A COOLED SHIELD IN A CRYOGENIC INSULATION *)
(* SYSTEM WHOSE THERMAL CONDUCTIVITY HAS THE FORM *)
(* K = E1*T^M) ON THE HOT SIDE *)
(* K = E2*T^N) ON THE COLD SIDE *)
(* THE METHOD IS BASED ON THE MINIMIZATION OF THE *)
(* ENTROPY PRODUCTION RATE WHICH IS PROPORTIONAL TO *)
(* THE HEAT LEAK ACROSS THE INSULATION *)
)

VAR

P REAL (* SHIELD / COLD WALL TEMPERATURE RATIO, ALWAYS > 1 *)
SMAI REAL (* MAXIMUM ENTROPY PRODUCTION RATE BASED ON E1*T^M *)
SMAII REAL (* MAXIMUM ENTROPY PRODUCTION RATE BASED ON E1*T^M *)
SMN REAL (* MINIMUM ENTROPY PRODUCTION RATE BASED ON E1*T^M *)
SMNI REAL (* MINIMUM ENTROPY PRODUCTION RATE BASED ON E1*T^M *)
TOTAL REAL (* TOTAL DIMENSIONLESS ENTROPY PRODUCTION RATE *)
SHE REAL (* DIMENSIONLESS ENTROPY PRODUCTION RATE AT SHIELD *)
C TOTAL REAL (* COLD WALL / HOT WALL TEMPERATURE RATIO, ALWAYS < 1 *)
C TOTAL REAL (* SHIELD / HOT WALL TEMPERATURE RATIO, ALWAYS < 1 *)
D REAL (* DISTANCE FROM COLD WALL / THICKNESS RATIO *)
D REAL (* X / (1 - D) *)

COUNT INTEGER (* NUMBER OF ITERATIONS NEEDED TO DETERMINE TCH *)
ALFA REAL (* DUMMY VARIABLE *)
D REAL (* DUMMY VARIABLE *)
E1 REAL (E1*(K-1)/(K-1)) (* DUMMY VARIABLES *)
M INTEGER (* INDEX TO TERMINATE THE SEARCH FOR TCH *)
MF REAL (* POWER OF THE THERMAL CONDUCTIVITY ON HOT SIDE *)
MF REAL (* POWER OF THE THERMAL CONDUCTIVITY ON COLD SIDE *)
N REAL (* EQUALS M-1 *)
P REAL (* HEAT IN AT COLD WALL *)
Q REAL (* HEAT OUT AT COLD WALL *)
P REAL (* ENTROPY PRODUCTION RATE AT COLD WALL *)
SCREAL (* OUTPUT FILE TO BE USED IF DESIRED *)
TM REAL (* NOT WALL TEMPERATURE (K) *)
PROCEDURE INPUTh:
BEGIN
WRITELN;
WRITELN(' ENTER ----> M M ALFA P THOT (----->)
WRITELN(')
WHERE.
ALFA ----- EXP(RH1)/EXP(RH2)4.
P ------- SHIELD / COLD WALL TEMPERATURE RATIO, ALWAVS > 1 4.
THOT ------ HOT WALL TEMPERATURE 4.
END.

PROCEDURE PFCH.
BEGIN
WRITELN;
WRITELN(' TO PERFORM COMPUTATION. ENTER 1 OTHERWISE, ENTER 0 4.
END.

PROCEDURE SINGLESPACE.
BEGIN
WRITELN(' SINGLE SPACE IN OUTPUT 4.
END.

FUNCTION PWR II.E REAL, REAL.
VAR
A.
BEGIN
A = EXPII.
PWR = EXP(A).
END.

FUNCTION DII.E REAL, REAL.
BEGIN
DII = FUNCTION D.
END.

FUNCTION FI.E REAL, REAL.
BEGIN
F = FUNCTION F.
END.

* MAIN PROGRAM BODY *
BEGIN
PFC;
READLN;
READI.
READPFC:
WHILE PFC = 0 DO
BEGIN
(* THIS BLOCK IS USED TO INPUT THE TWO INSULATION THERMAL CONDUCTIVITIES. *)
(* SHIELD / COLD WALL TEMPERATURE RATIO AND HOT WALL TEMPERATURE *)
INPUTh.
READI.
READI.M ALFA,P, THOT),
SINGLESPACE.
WRITELN(' THERMAL CONDUCTIVITY OF THE INSULATION ON THE HOT SIDE IS \( k = \exp(1) \cdot \exp(-1) \cdot \exp(1) \).')
WRITELN(' THERMAL CONDUCTIVITY OF THE INSULATION ON THE COLD SIDE IS \( k = \exp(1) \cdot \exp(-1) \cdot \exp(1) \).')
WRITELN(' \exp(1) \cdot \exp(-1) \cdot \exp(1) \cdot A\LFA, P, THOT.);
ORIGINAL PAGE IS OF POOR QUALITY

(* THIS BLOCK CALCULATES TCH ITERATIVELY *)

REPEAT
175 TSH = TSH + TCH.
176 G = D(N,P) * D(M,P) / D(M,TSH) / D(N,TSH) / ALFA.
177 GI = G0.
178 IF GI < 0.3 THEN GOTO 100.
179 IF GI = 0 THEN GOTO 100.
180 CC = (-0.11) * CC.
181 IF ABS(CC) < 0.00001 THEN GOTO 100.
182 DD = DD.
183 IF 'TCH:0.000001' OR (TCH(000001)) THEN BEGIN
184 TCH = TCH - TCH CC.
185 CC = -CC.
186 IF ABS(CC) < 0.00001 THEN IND = 1.
187 END.
188 COUNT = COUNT + 1.
189 UNTIL (GI < 0.1) OR (ABS(CC) < 0.00001) OR (IND = 1).

IF IND = 1 THEN BEGIN
194 SINGLESPACE.
195 SINGLESPACE.
196 SINGLESPACE.
197 SINGLESPACE.
198 SINGLESPACE.
199 SINGLESPACE.
199 REWRITE
--- OBTIMUM CRITERION CANNOT BE SATISFIED
--- USE SINGLE INSULATION WITH THE LOWER CONDUCTIVITY
100 GOTO 300.
201 END.

(* OTHER QUANTITIES OF INTEREST ARE COMPUTED IN THIS SECTION *)

I = ALFA + PVW(TCH, M-1) / (D(M,P) / D(M,TSH))
202 IF X < 0.1 THEN 203.
203 GQOT = (1 - PVW(TSH, M)) / (1 - XMP)).
204 GQCD = ALFA + PVW(TCH, M) / (PVW, N) / (1 - 1 / PVW(TCH, M)) / MP1.
205 GCOLD = GQCD + TCH.
206 STOTA = F (TCH, M) / (X + ALFA + PVW(TCH, M) / (F(N,P) / X))
207 SCOLD = STOTA - TCH.
208 IF SCOLD < 0 THEN 209.
209 SMN1 = SORLN / (1 / TCH).
210 ELSE
211 SMN2 = SORLN / (1 / TCH).
212 IF X = 0 THEN 213.
213 SMNI = SORLN / (1 / TCH)
214 ELSE
215 SMNI = SORLN / (1 - PVW(TCH, M) / (X / 0)) / (X / 0))
216 SMNI = SORLN / (1 / TCH).
217 ELSE
218 SMNI = SORLN / (1 - PVW(TCH, M) / (X / 0)) / (X / 0))
219 SMNI = SORLN / (1 / TCH)
220 SNA1 = F (TCH, M) / MP1.
221 SNA1 = F (TCH, MP1).
222 SNAI = F (TCH, MP1).

SINGLESPACE.

224 REWRITE
NUMBER OF ITERATIONS = COUNT.
225 REWRITE
COLD WALL / HOT WALL TEMPERATURE RATIO = TCH.
226 REWRITE
SHIELD / HOT WALL TEMPERATURE RATIO = TSH.
227 REWRITE
SHIELD LOCATION = X.
228 REWRITE
HEAT OUT AT SHIELD = QOT - GCOLD.
229 REWRITE
HEAT OUT AT COLD WALL = GCOLD.
230 REWRITE
HEAT IN AT HOT WALL = QOT.
231 REWRITE
ENTROPY PRODUCTION RATE AT COLD WALL = SCOLD.
232 REWRITE
ENTROPY PRODUCTION RATE AT HOT WALL = QOT.
233 REWRITE
ENTROPY PRODUCTION RATE AT SHIELD = SISH.
234 REWRITE
MINIMUM ENTROPY PRODUCTION RATE BASED ON X1*1**N = SINI.
235 REWRITE
MINIMUM ENTROPY PRODUCTION RATE BASED ON X1*1**N = SINI.
236 REWRITE
TOTAL ENTROPY PRODUCTION RATE = STOTAL.
237 REWRITE
ENTROPY PROD W/O SHIELD BASED ON X1*1**N = SNAI.
TO PERFORM COMPUTATION, ENTER 1. OTHERWISE, ENTER 0.

ENTER ----> M N ALFA P THOT -----

WHERE: M ------ POWER OF THE THERMAL CONDUCTIVITY EQUATION ON THE HOT SIDE
N ------ POWER OF THE THERMAL CONDUCTIVITY EQUATION ON THE COLD SIDE
ALFA -- [(K2*(M+1)))/(K1*(N+1))]
P ------ SHIELD / COLD WALL TEMPERATURE RATIO, ALWAYS = 1
THOT -- HOT WALL TEMPERATURE [K]

1.0  0.0  20.0  4.5  300.0

THERMAL CONDUCTIVITY OF THE INSULATION ON THE HOT SIDE IS K = K1*(T**M).
THERMAL CONDUCTIVITY OF THE INSULATION ON THE COLD SIDE IS K = K2*(T**N).

K2*(M+1)/K1*(N+1) = 20.0
HOT WALL TEMPERATURE = 300.00 [K]

NUMBER OF ITERATIONS = 36
COLD WALL / HOT WALL TEMPERATURE RATIO = 0.0016666
SHIELD / HOT WALL TEMPERATURE RATIO = 0.007497
SHIELD LOCATION = 0.390755
HEAT OUT AT SHIELD = 0.820144
HEAT OUT AT COLD WALL = 0.820641
HEAT IN AT HOT WALL = 0.820641
ENTROPY PRODUCTION RATE AT COLD WALL = 0.298568
ENTROPY PRODUCTION RATE AT HOT WALL = -0.820641
ENTROPY PRODUCTION RATE AT SHIELD = 109.396253
MINIMUM ENTROPY PRODUCTION RATE BASED ON K1*T**M = 3.680131
MINIMUM ENTROPY PRODUCTION RATE BASED ON K2*T**N = 40.925828
TOTAL ENTROPY PRODUCTION RATE = 178.307751
ENTROPY PROD. W/O SHIELD BASED ON K1*T**M = 299.619216
ENTROPY PROD. W/O SHIELD BASED ON K2*T**N = 598.241762

TO PERFORM COMPUTATION, ENTER 1. OTHERWISE, ENTER 0.

0.044 CP SECS, 10233B CM USED.
A relatively simple method has been developed to optimize the location, temperature, and heat dissipation rate of each cooled shield inside an insulation layer. The method is based on the minimization of the entropy production rate which is proportional to the heat leak across the insulation. The results show that the maximum number of shields to be used in most practical applications is three. However, cooled shields are useful only at low values of the overall, cold wall to hot wall absolute temperature ratio. The performance of the insulation system is relatively insensitive to deviations from the optimum values of the temperature and location of the cooling shields.

Design curves are presented for rapid estimates of the locations and temperatures of cooling shields in various types of insulations, and an equation is given for calculating the cooling loads for the shields.
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