1961

Transpiration cooling

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Department:

TRANSPIRATION COOLING

BY

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A

THESIS

submitted to the faculty of the

SCHOOL OF MINES AND METALLURGY OF THE UNIVERSITY OF MISSOURI

in partial fulfillment of the work required for the

Degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

Rolla, Missouri

1961

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I. ABSTRACT

In the investigation of the problem, it is shown that the process of transpiration cooling is an effective method of cooling. This process may be applied to heat screens or heat shields, as was done in the sample problems worked out here. A porous plate with coolant flowing counter to the flow of heat was used.

The plate temperature is determined by the amount of heat flux, coolant flow, thermal conductivity of the material used as a plate, the specific heat of the fluid, the specific heat of the plate material, the density of the plate material and its porosity. In the steady state, the maximum temperature at the surface is dependent only on the heat flux and the mass flow rate of the coolant.

The mass flow rate and specific heat of the coolant are the most critical factors in controlling the plate temperatures. It should be emphasized that the values used in the sample problems solved here are arbitrarily chosen and by no means should they be considered as optimum conditions. It is evident from the small temperature rise (94.8^{o}F), of the first sample problem, that the mass flow of the coolant is greater than is required for the materials used.

Liquids may also be used as fluids for cooling. When liquids are used the heat required to vaporize the liquid also tends to lower the temperature of the plate, however, this gives rise to additional problems in pumping

and pressure drops through the plate, to say nothing of the changes in volume due to vaporization of the liquid.

The plate temperature decreases rapidly after a short distance in the plate. Therefore this process with properly selected materials, would seem to have many applications in industry and research. Applying this process to heat screens or shields would allow thin plates to be used.

The potential of this method of cooling seems, to the author, to be great.

II. ACKNOWLEDGEMENT

The author wishes to thank Dr. A.J. Miles for his assistance and for suggesting the thesis subject. The author also wishes to thank William H. Stocklin for his assistance in the programming of this problem.

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III. INTRODUCTION

Due to the increasing use of higher and higher temperatures in reactors, missile applications and high temperature furnaces, there has developed a need for materials to withstand these elevated temperatures So far these new materials have not been forthcoming, at least not in commercial quantities. Therefore, it becomes necessary to devise methods of using available materials at elevated temperatures. One method by which this may be accomplished is by the use of heat shields or screens. Heat shields and heat screens will be used synonymously in this problem. A heat shield is defined as an object used to protect or reduce the amount of heat reaching some point. Transpiration cooling, by passing a coolant through a porous plate, would seem to have possibilities as a heat shield. A condition of high constant heat flux was selected for investigation, as this is a common condition, assumed in many heat transfer problems.

Cooling of a porous plate by passing cool gas through it has long been suggested as an effective method of cooling, however, only recently has the problem of constant heat flux to the plate surface been considered. This type of problem is a consideration where large amounts of radiation are present, as in outer space, high temperature furnaces, jet engines, gas turbines, etc.

The problem selected for investigation in this thesis is that of a porous plate receiving a constant heat flux on one surface, while cool fluid is forced through the plate from the opposite side. The temperature of the plate is initially the temperature of cool fluid. This plate is exposed to a heat flux and begins heating up. It is this transient heat condition that is of interest in this problem. Heat conduction through both the solid and fluid are considered. Change in internal energy due to the rise in temperature is also considered in both the solid and fluid.

A number of assumptions are made in order to simplify the solution of this problem. These are assumptions which are commonly made in engineering applications of heat transfer problems.

The assumptions involved in this problem are summarized as follows:

1) In the porous plate, gas temperature and solid temperature at a point are approximately equal.
2) The gas flow is steady and one-dimensional. Convective effects neglected by this assumption will not alter the temperature distribution in the plate to any appreciable extent.
3) The thermal conductivities and specific heats of the solid and gas are constant.

The problem then is to devise a method for determining the transient temperature distribution in a porous plate using numerical methods. Since most industries have their own computers or have access to computers for their use, this method becomes a practical one. By writing a general program that may be used with various sets of data, it becomes a simple matter to change the data as desired and obtain solutions for any number of similar problems. The methods of numerical analysis are approximate, however, for most engineering work this is sufficient.

The nomenclature used in this problem is as follows:

C_p = Specific heat of coolant (BTU/lb ^{o}F)

C = Specific heat of solid (BTU/lb ^{o}F)

K = Thermal conductivity of solid (BTU/ft^2 hr ^{o}F/ft)

Q = Heat flux (BTU/hr ft^2)

A = Cross Sectional Area (ft^2)

P = Porosity $\frac{\text{Pore Volume}}{\text{Total Volume}}$

t = Temperature (^{o}F)

t' = Temperature after some time increment (^{o}F)

δ = Distance between nodes (ft)

G = Mass flow rate (lbs/hr ft^2)

ρ = Specific weight of solid (lbs/ft^3)

ρ_f = Specific weight of coolant (lbs/ft^3)

K_f = Thermal conductivity of coolant (BTU/ft^2 hr ^{o}F/ft)

V = Volume of section considered (ft^3)

$\Delta\theta$ = Time increment (hr)

IV. REVIEW OF LITERATURE

The process of solid-fluid heat transfer in transpiration cooling is quite complex, therefore the simplifying assumptions were made. Weinbaum and Wheller (1) have demonstrated that the solid and fluid temperatures are nearly indistinguishable throughout the porous material.

Weinbaum and Wheller (1) considered, as most authors in the past, only the steady state conditions, neglecting the transient conditions completely. By using an iteration process similar to the Gauss-Seidel Method as found in Hildebrand (2), it is possible to have a temperature history of the wall. A family of curves may be plotted to show temperature distribution in the plate at various times.

Schneider (3) gives a very brief explanation of using numerical methods in problems of this type, but does not go into any detail. A much better idea of the possible numerical methods may be found in Hildebrand (2) or in Kunz (4). There are a great many references in this field which might have been used. For a list of these see Appendix 1.

The problem of mass transfer in using a liquid as a fluid, is touched on in Eckert and Drake (5), but not specifically dealing with this type of problem. It is rather difficult to find much material on the subject in any one place, therefore a number of references were used. A paper by Green (6) gives a good discussion of gas cooling of a heat source. He used a generating plate of graphite which was cooled by helium. He did work on pressure drops and the pumping of fluids.

Much of the work done on the computer used methods given by Lee (7) in his notes to a Numerical Analysis and Digital Computers class (Math 318). Personal consultation with professor Lee proved to be very helpful. All physical data for the materials used was taken from Marks Mechanical Engineering Handbook (8). All data required may be found in this reference. A general review of heat transfer was taken from Gebhart (9) as this is a new book and it was thought that possibly some new work might have been covered in this text.

V. DISCUSSION

Consider the plate in Fig. 1 below. Heat is entering from the left at a constant rate, while cool gas is being passed through the plate from the right.

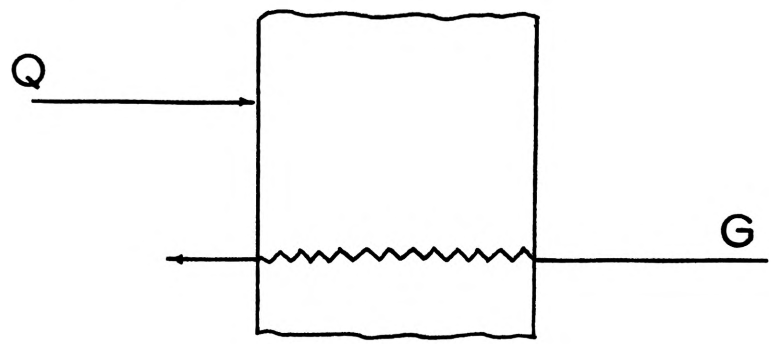

FIG. 1

The plate in Fig. 1 was divided into three full sections and two half sections with five nodes as in Fig. 2. This is done because surface temperatures are required. By using half sections at the surfaces the temperatures at the surfaces are found. A discussion of this may be found in Schneider (3), also Schneider (3) points out that five nodes should be sufficient for problems of this type.

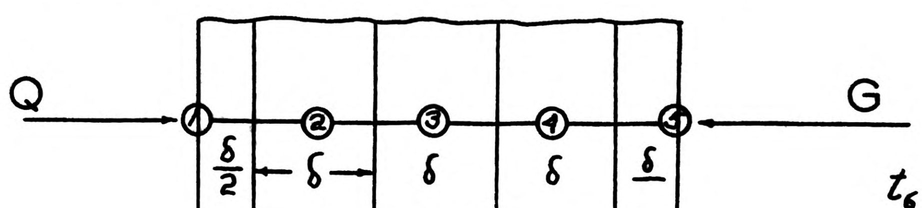

FIG. 2

Heat balances for each of the five points were then written. They are as follows: For point 1

$$AQ\Delta\theta = A\Delta\theta\left[GC_p(t_1-t_2) + \frac{K(1-P)}{\delta}(t_1-t_2) + \frac{K_f P}{\delta}(t_1-t_2)\right]$$
$$+\rho\frac{V}{2}(1-P)C(t_1'-t_1) + \rho_f\frac{V}{2}PC_p(t_1'-t_1) .$$

The terms in this equation are defined as follows:

The heat flux entering the small surface area during the time increment = $AQ\Delta\theta$;

The amount of heat given up to the coolant by the solid = $A\Delta\theta GC_p(t_1 - t_2)$;

Conduction away from point 1 through the solid =

$$A\Delta\theta \frac{K(1-P)}{\delta}(t_1 - t_2);$$

Conduction away from point 1 through the coolant =

$$A\Delta\theta \frac{K_f P}{\delta}(t_1 - t_2);$$

The increase in internal energy of the solid =

$$\rho \frac{V}{2}(1-P)C(t_1' - t_1);$$

The increase in internal energy of the coolant

$$\rho_f \frac{V}{2} PC_p(t_1' - t_1).$$

$\frac{V}{2}$ is used in the equation because a con tant cross-sectional area is being considered in this problem, and since half sections are being used at the surfaces, half volumes must be used.

Assuming that the temperature of the porous plate at time zero to be uniform and at the temperature of the incoming coolant, the only unknown in the equation becomes t_1'. Solving for t_1', the equation becomes

$$t_1' = \frac{AQ\Delta\theta - A\Delta\theta\left[GC_p + \frac{K(1-P)}{\delta} + \frac{K_f P}{\delta}\right](t_1 - t_2)}{\left[\rho \frac{V}{2}(1-P)C + \rho_f \frac{V}{2} PC_p\right]} + t_1,$$

t_1' being the temperature of point 1 after the first time increment.

A heat balance was then written for point 2. The first term $AQ\Delta\theta$ was not present in this heat balance, however, two additional conduction terms for the heat entering are now included, and are as follows:

Heat entering point 2 by conduction through the solid=

$A\Delta\theta \frac{K(1-P)}{\delta}(t_1-t_2)$;

Heat entering point 2 by conduction through the coolant=

$A\Delta\theta \frac{K_f P}{\delta}(t_1-t_2)$.

The remaining terms are very similar to those of point 1, except a full volume is used instead of a half volume. They are as follows:

Heat leaving point 2 by conduction through the solid=

$A\Delta\theta \frac{K(1-P)}{\delta}(t_2-t_3)$;

Heat leaving point 2 by conduction through the coolant=

$A\Delta\theta \frac{K_f P}{\delta}(t_2-t_3)$;

Heat give up to the coolant by the solid.=

$A\Delta\theta G C_p (t_2-t_3)$;

The increase in internal energy of the solid=

$\rho V(1-P)C(t_2'-t_2)$;

The increase in internal energy of the coolant=

$\rho_f V P C_p (t_2'-t_2)$.

Therefore the heat balance for point 2 becomes

$$A\Delta\theta\left[\frac{K(1-P)}{\delta}+\frac{K_f P}{\delta}\right](t_1-t_2) - A\Delta\theta\left[GC_p+\frac{K(1-P)}{\delta}+\frac{K_f P}{\delta}\right](t_2-t_3)$$

$$= \rho V(1-P)C(t_2'-t_2) + \rho_f V P C_p (t_2'-t_2).$$

As in the heat balance for point 1, the only unknown is t_2'. Solving for t_2'

$$t_2' = \frac{A\Delta\theta\left[\frac{K(1-P)}{\delta} + \frac{K_f P}{\delta}\right](t_1 - t_2) - A\Delta\theta\left[GC_p + \frac{K(1-P)}{\delta} + \frac{K_f P}{\delta}\right](t_2 - t_3)}{\left[\rho V(1-P)C + \rho_f VPC_p\right]} + t_2 .$$

The same procedure was followed for point 3 and point 4 with the following results.

$$t_3' = \frac{A\Delta\theta\left[\frac{K(1-P)}{\delta} + \frac{K_f P}{\delta}\right](t_2 - t_3) - A\Delta\theta\left[GC_p + \frac{K(1-P)}{\delta} + \frac{K_f P}{\delta}\right](t_3 - t_4)}{\left[\rho V(1-P)C + \rho_f VPC_p\right]} + t_3$$

and

$$t_4' = \frac{A\Delta\theta\left[\frac{K(1-P)}{\delta} + \frac{K_f P}{\delta}\right](t_3 - t_4) - A\Delta\theta\left[GC_p + \frac{K(1-P)}{\delta} + \frac{K_f P}{\delta}\right](t_4 - t_5)}{\left[\rho V(1-P)C + \rho_f VPC_p\right]} + t_4 .$$

The heat balance for point 5 does not contain a term for conduction away through the solid and uses half volumes as it is a surface point. Following the same procedure and solving for t_5', we have

$$t_5' = \frac{A\Delta\theta\left[\frac{K(1-P)}{\delta} + \frac{K_f P}{\delta}\right](t_4 - t_5) - A\Delta\theta\left[\frac{K_f P}{\delta} + GC_p\right](t_5 - t_6)}{\left[\rho \frac{V}{2}(1-P)C + \rho_f \frac{V}{2} PC_p\right]} + t_5 .$$

By grouping the constant terms we have,

$$W = \frac{AQ\Delta\theta}{\left[\rho \frac{V}{2}(1-P)C + \rho_f \frac{V}{2} P C_p\right]},$$

$$X = \frac{A\Delta\theta\left[GC_p + \frac{K(1-P)}{\delta} + \frac{K_f P}{\delta}\right]}{\left[\rho \frac{V}{2}(1-P)C + \rho_f \frac{V}{2} P C_p\right]},$$

$$Y = \frac{A\Delta\theta\left[\frac{K(1-P)}{\delta} + \frac{K_f P}{\delta}\right]}{\left[\rho V(1-P)C + \rho_f V P C_p\right]},$$

$$Z = \frac{A\Delta\theta\left[GC_p + \frac{K(1-P)}{\delta} + \frac{K_f P}{\delta}\right]}{\left[\rho V(1-P)C + \rho_f V P C_p\right]},$$

$$U = \frac{A\Delta\theta\left[\frac{K(1-P)}{\delta} + \frac{K_f P}{\delta}\right]}{\left[\rho \frac{V}{2}(1-P)C + \rho_f \frac{V}{2} P C_p\right]} \quad \text{and}$$

$$V = \frac{A\Delta\theta\left[GC_p + \frac{K_f P}{\delta}\right]}{\left[\rho \frac{V}{2}(1-P)C + \rho_f \frac{V}{2} P C_p\right]}$$

The equations for the temperature after the first time increment are,

$$t_1' = W - X(t_1 - t_2) + t_1 ,$$

$$t_2' = Y(t_1 - t_2) - Z(t_2 - t_3) + t_2 ,$$

$$t_3' = Y(t_2 - t_3) - Z(t_3 - t_4) + t_3 ,$$

$$t_4' = Y(t_3 - t_4) - Z(t_4 - t_5) + t_4 \quad \text{and}$$

$$t_5' = U(t_4 - t_5) - V(t_5 - t_6) + t_5 .$$

From the preceding equations, t_1', t_2', t_3', t_4' and t_5' can be found as the initial temperatures are known. Using these values, t_1'', t_2'', t_3'', t_4'' and t_5'' can then be found. These new temperatures can then be used in the same process to find five new temperatures. This process is continually repeated until steady state conditions are reached. Using this process, any combination of gas flow, material and heat flux may be used.

To illustrate the method, two sample problems are worked out. Heat flux of 50,000 BTU/hr ft^2 and 1,500,000 BTU/hr ft^2 was selected to show the range over which this process was practical. A mass flow, G, of 2,000 lbs/hr ft^2 was selected, since using this flow allowed a large temperature range to be investigated and it required a velocity of approximately 7.5 ft/sec. A one-inch plate was selected as convenient and since five nodes were being used (see Fig. 2), this caused δ to be one-quarter of an inch. A constant square cross-sectional area and a cubic shaped volume are used. Air was used as a fluid and a high alumina refractory was selected as a porous plate. The following physical properties of these materials were found in Marks Mechanical Engineering Handbook.

$C_p = .25$ BTU/lb ^oF

$C = .23$ BTU/lb ^oF

$K = 1$ BTU/ft^2 hr ^oF

$K_f = .033$ BTU/ft^2 hr ^oF

$P = .25$

ρ= 128 lbs/ft^3

ρ_f= .0753 lbs/ft^3

Values of initial temperature and time increment were arbitrarily selected. Area and volume are listed below with the values of temperature and time.

$\delta = 1/4" = 1/48$ ft

$A = \delta\delta = 1/48 \; 1/48 \; ft^2$

$V = \delta\delta\delta = 1/48 \; 1/48 \; 1/48 \; ft^3$

$t_1 = t_2 = t_3 = t_4 = t_5 = t_6 = 100\ ^oF$

$\Delta\theta = 1$ Sec $= \frac{1}{3600}$ hr

Using these values, the constants W,X,Y,Z,U,V, are as follows:

	for 50,000 BTU/hr ft^2	for 1,500,000 BTU/hr ft^2
W =	60.3736059	1811.208177
X =	.647650712	.647650612
Y =	.0219572767	.0219572767
Z =	1.295301224	1.29 301224
U =	.0109786383	.0109786383
V =	.604181616	.604181616

Originally a fixed point program was written to solve this problem, however, after running several programs, in which errors were ma e, it was decided to write the program in the 24.2 floating point interpretive system. This is much simpler to write though much slower to run. These programs ran about thirty minutes each. With other flow rates and materials, more time may be needed for similar problems.

FLOW CHART FOR COMPUTER

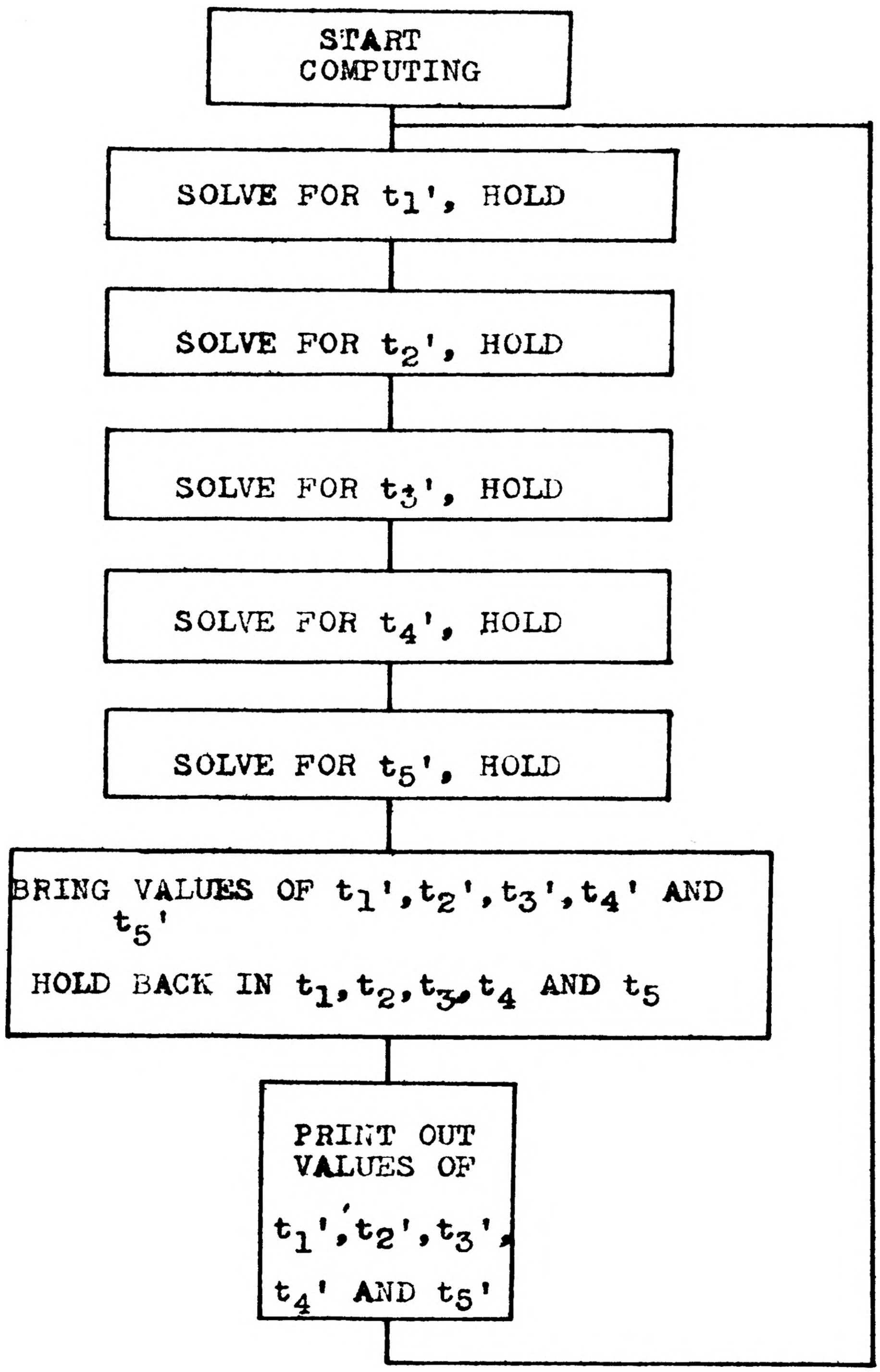

FIG. 3

COMPUTER PROGRAM FOR ROYAL MCBEE LGP-30 DIGITAL COMPUTER

```
;0004800'/0000000'

r6300'u0400'i5000'b5012's5014'm5002'h5200'b5000'
s5200'a5012'h5202'b5014's5016'm5006'h5204'b5012'
s5014'm5004's5204'a5014'h5206'b5016's5018'm5006'
h5208'b5014's5016'm5004's5208'a5016'h5210'b5018'
s5020'm5006'h5212'b5016's5018'm5004's5212'a5018'
h5214'b5020's5022'm5010'h5216'b5018's5020'm5008'
s5216'a5020'h5218'b5202'h5012'p5012'd0000'b5206'
h5014'p5014'd0000'b5210'h5016'p5016'd0000'b5214'
h5018'p5018'd0000'b5218'h5020'p5020'm0000'u4803'

.0004800'

60373605'+06-'64765061'+08-'21957276'+09-'12953012'+07-'
10978638'+09-'60418161'+08-'100''100''100''100''100''
100''f'
```

FIG. 4

COMPUTER PROGRAM FOR ROYAL MCBEE LGP - 30 DIGITAL COMPUTER

```
;0004800'/0000000'

r6300'u0400'i5000'b5012's5014'm5002'h5200'b5000'
s5200'a5012'h5202'b5014's5016'm5006'h5204'b5012'
s5014'm5004's5204'a5014'h5206'b5016's5018'm5006'
h5208'b5014's5016'm5004's5208'a5016'h5210'b5018'
s5020'm5006'h5212'b5016's5018'm5004's5212'a5018'
h5214'b5020's5022'm5010'h5216'b5018's5020'm5008'
s5216'a5020'h5218'b5202'h5012'p5012'd0000'b5206'
h5014'p5014'd0000'b5210'h5016'p5016'd0000'b5214'
h5018'p5018'd0000'b5218'h5020'p5020'm0000'u4803'

.0004800'

18112081'+04-'64765061'+08-'21957276'+09-'12953012'+07-'
10978638'+09-'60418161'+08-'100''100''100''100''100''
100''f'
```

FIG. 5

TEMPERATURE DISTRIBUTION IN A POROUS PLATE

(50,000 BTU/hr ft^2)

TABLE I

TIME SEC	TEMPERATURE °F NODE 1	NODE 2	NODE 3	NODE 4	NODE 5
0	100.00000	100.00000	100.00000	100.00000	100.00000
1	160.37360	100.00000	100.00000	100.00000	100.00000
2	181.64620	101.32564	100.00000	100.00000	100.00000
3	190.00014	101.37216	100.02910	100.00000	100.00000
4	192.97378	101.57853	100.02089	100.00064	100.00000
5	194.15519	101.56771	100.02886	100.00025	100.00000
6	194.56446	101.60740	100.02560	100.00056	100.00000
7	194.73437	101.59957	100.02790	100.00039	100.00001
8	194.78916	101.60877	100.02677	100.00050	100.00001
9	194.81443	101.60560	100.02747	100.00044	100.00001
10	194.82128	101.60806	100.02710	100.00047	100.00001
11	194.82529	10 .60695	100.02732	100.00045	100.00001
12	194.82598	101.60767	100.02720	100.00046	100.00001
13	194.82669	101.60731	100.02727	100.00046	100.00001
14	194.82671	101.60753	100.02723	100.00046	100.00001
15	194.82685	101.60741	100.02725	100.00046	100.00001
16	194.82683	101.60748	100.02724	100.00046	100.00001
17	194.82686	101.60744	100.02725	100.00046	100.00001
18	194.82685	101.60746	100.02724	100.00046	100.00001
19	194.82686	101.60745	100.02725	100.00046	100.00001
20	194.82686	101.60746	100.02725	100.00046	100.00001
21	194.82686	101.60745	100.02725	100.00046	100.00001
22	194.82686	101.60745	100.02725	100.00046	100.00001

TEMPERATURE DISTRIBUTION IN A POROUS PLATE

(1,500,000 BTU/hr ft^2)

TABLE II

TIME	TEMPERATURE °F				
SEC	NODE 1	NODE 2	NODE 3	NODE 4	NODE 5
0	100.00000	100.00000	100.00000	100.00000	100.00000
1	1911.2081	100.00000	100.00000	100.00000	100.00000
2	2549.3861	139.76919	100.00000	100.00000	100.00000
3	2800.0043	141.16473	100.87322	100.00000	100.00000
4	2889.2133	147.35596	100.62683	100.01917	100.00000
5	2924.6558	147.03137	100.86577	100.00768	100.00021
6	2936.9337	148.22208	100.76795	100.01684	100.00016
7	2942.0310	147.98720	100.83700	100.01173	100.00025
8	2943.6749	148.26309	100.80332	100.01498	100.00022
9	2944.4328	148.16802	100.82427	100.01318	100.00025
10	2944.6383	148.24196	100.81320	100.01424	100.00024
11	2944.7586	148.20868	100.81971	100.01365	100.00025
12	2944.7794	148.23031	100.81615	100.01399	100.00024
13	2944.8008	148.21929	100.81820	100.01380	100.00025
14	2944.8011	148.22591	100.81706	100.01391	100.00024
15	2944.8056	148.22234	100.81770	100.01385	100.00025
16	2944.8048	148.22441	100.81734	100.01388	100.00025
17	2944.8059	148.22327	100.81755	100.01386	100.00025
18	2944.8055	148.22392	100.81743	100.01387	100.00025
19	2944.8058	148.22355	100.81750	100.01387	100.00025
20	2944.8057	148.22376	100.81746	100.01387	100.00025
21	2944.8058	148.22364	100.81748	100.01387	100.00025
22	2944.8057	148.22371	100.81747	100.01387	100.00025
23	2944.8058	148.22367	100.81748	100.01387	100.00025
24	2944.8058	148.22369	100.81747	100.01387	100.00025
25	2944.8058	148.22368	100.81747	100.01387	100.00025
26	2944.8058	148.22369	100.81747	100.01387	100.00025
27	2944.8058	148.22369	100.81747	100.01387	100.00025

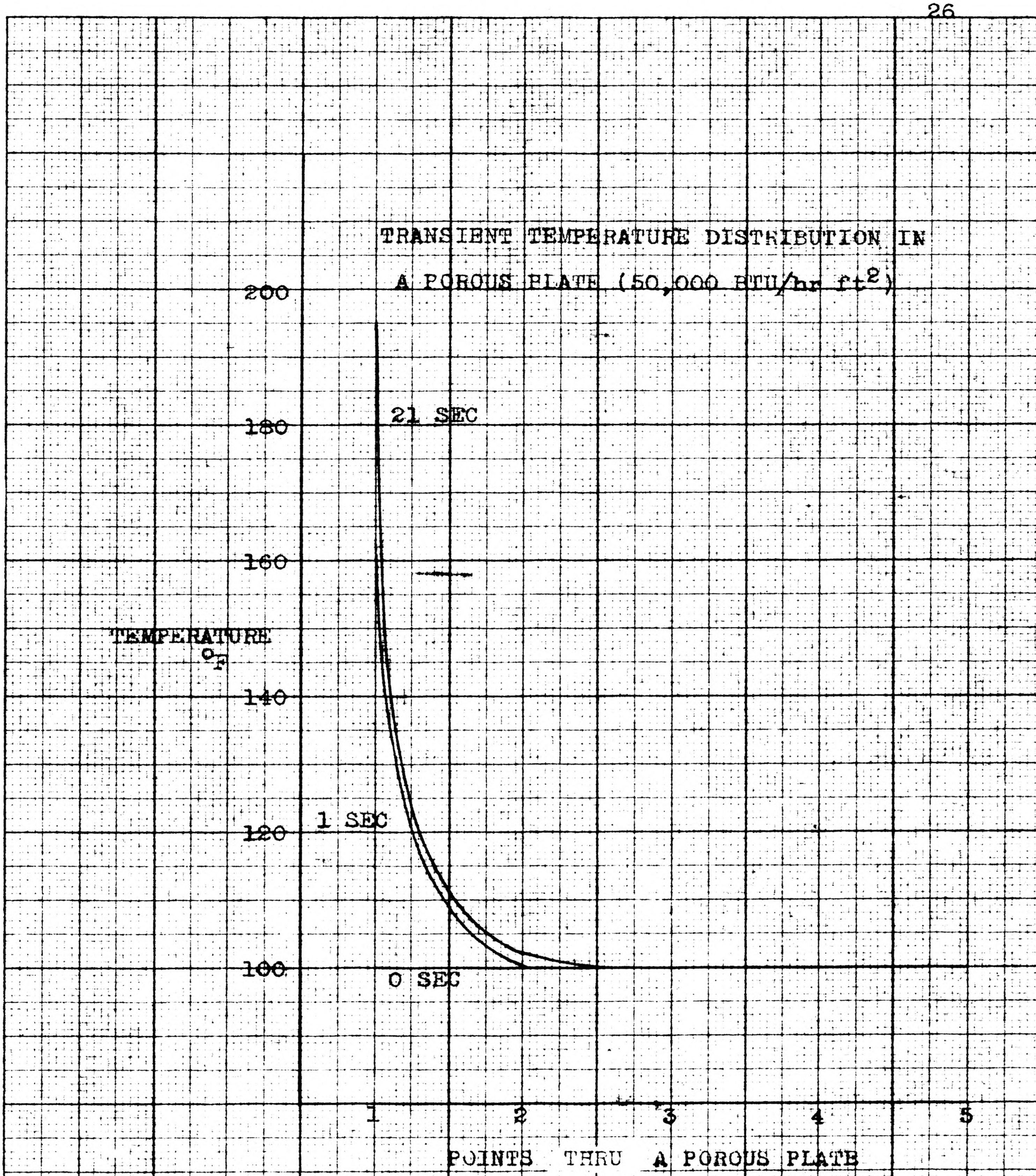
TRANSIENT TEMPERATURE DISTRIBUTION IN
A POROUS PLATE (50,000 BTU/hr ft^2)
200
180
160
140
120
100
21 SEC
1 SEC
0 SEC
TEMPERATURE
°F
1
2
3
4
5
POINTS THRU A POROUS PLATE

FIGURE 6

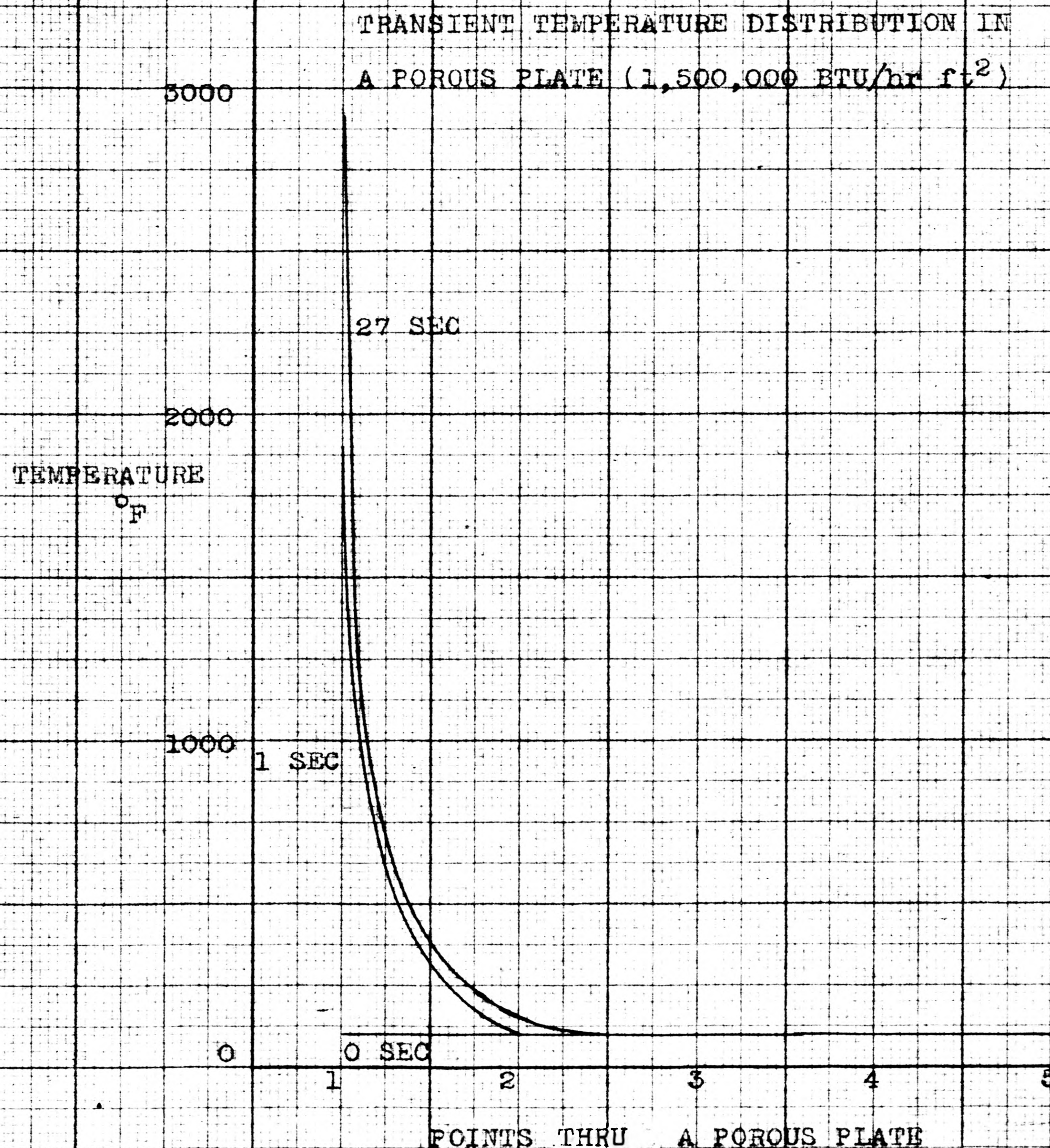
TRANSIENT TEMPERATURE DISTRIBUTION IN
A POROUS PLATE (1,500,000 BTU/hr ft²)
3000
2000
1000
0
TEMPERATURE
°F
27 SEC
1 SEC
0 SEC
1
2
3
4
5
POINTS THRU A POROUS PLATE

FIGURE 7

A sample of the results of the calculations done by the computer can be found in Table I and II. These samples are taken at various intervals to give a better picture of what is taking place. A record of the transient temperature distribution as completed by the computer may be found for any time.

The time to reach stabilization in these sample problems is quite short, however, in other similar problems the time may be considerably longer. This time is controlled for the most part by the flow rates used and the specific heat of the coolant.

A plot of selected temperature distribution, as shown in Figs. 6 and 7, shows that most of the heat is picked up by the coolant, a very short distance from the hot surface.

VI. CONCLUSIONS

The method of approaching the solution to the problem of transient heat conditions has long been known, however, until the recent advent of high speed computers, the time involved in obtaining solutions has been prohibitive. With computers available in many industries many problems that have not been consid red before may now be solved practically and economically.

The problem of transpiration cooling is a recent one and though some work has been done in this area, it has been limited to steady state conditions. Experimental work would be of much assistance in proving or disproving many of the assumptions made in the solving of transpiration cooling problems.

From the sample problem worked out in this thesis, it would seem that a great deal of work should be done in this area because transpiration cooling seems to have great potential for use as heat shields and screens. With proper selection of materials and flow rates, temperatures can be controlled effectively. Most of temperature drop occurs within a short distance from the heated surface. Therefore thin plates may be used, effectively cutting down on the cost of material and especially important in the aircraft or missile industries, the weight of material needed. Some of the need for high temperature materials may be eliminated by use of porous materials.

One example where the properties of transpiration cooling has a practical application is that of a high temperature furnace. The fuel could enter through the side of the combustion chamber, which would be made of a porous material. The combustion air could then be forced through the porous walls of the combustion chamber thereby cooling the walls and preheating the combustion air at the same time. A furnace of this type should be efficient and practical. An outer shell of steel would only have to contain the combustion air.

The transient condition is of short duration, in this case a little more than twenty seconds. It is of importance in determining thermal stresses in the porous medium because of the extreme unequal temperature existing at adjacent points.

In the area of future work more precise solutions should be worked out, including many of the factors that have been neglected in the past. Fewer assumptions should be made when working out solutions. Some experimental work should be done to verify both solutions and assumptions.

With some knowledge of numerical analysis, many problems of this type may be solved in a comparatively short time.

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VIII. APPENDIX 1

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IX. VITA

Herbert S. Brahinsky was born October 11, 1933, at St. Joseph, Missouri. He received his elementary and high school education in St. Joseph, Missouri. He also attended St. Joseph Junior College in St. Joseph, Missouri and received an Associate in Science Degree from there in 1953.

Shortly after receiving the degree he joined the United States Air Force and went into Cadet training. He received his wings on December 18, 1954, and was married December 18, 1954 to Miss Nellie Allen of Savannah, Missouri.

Their one son David was born on April 27, 1957 while they were still in the service. After discharge in November 1957, he returned to school at the Missouri School of Mines and Metallurgy where he received a Bachelor of Science Degree in Mechanical Engineering in May 1960. He immediately began graduate study at the Missouri School of Mines and Metallurgy.