research report

ANALYSIS OF PRESSURE DROP AND HEAT TRANSFER OF A PEBBLE-BED-STORAGE HEATER FOR A HYPERSONIC WIND TUNNEL

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May 1961

Sandia Corporation

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ABSTRACT

The pressure drop and the time-temperature variation of the air test medium and heat storage material in a pebble-bed heater (designed for intermittent hypersonic wind-tunnel operation at test section Mach numbers of 4 to 11) are presented.
NOMENCLATURE

A - Total cross-sectional area of pebble bed, \( \text{ft}^2 \)

a - Pebble-bed surface area per foot of depth, \( a = \frac{6A(1 - e)}{d} \), \( \text{ft}^2/\text{ft} \)

c - Specific heat of air, BTU/\( \text{lb}^0\text{F} \)

c_p - Specific heat of pebbles, BTU/\( \text{lb}^0\text{F} \)

D - Bed diameter, feet

d - Diameter of pebbles, feet

e - Porosity of pebble bed, e = ratio of void volume to total volume, dimensionless

(for \( \frac{D}{d} = 62, e = 0.33 \)), see Reference 5

g - Acceleration of gravity, \( \text{ft/sec}^2 \)

h_f - Film coefficient, \( h_f = 0.56 \frac{k}{d} \left( \frac{Re_f}{Pr} \right)^{0.6} (Pr)^{0.33} \), BTU/hr-ft^2-\(^0\text{R} \)

H - Heat transfer coefficient from pebbles to air, \( H = \frac{1}{h_f} + \frac{d}{2k_p} \) BTU/hr-ft^2-\(^0\text{R} \)

k - Coefficient of thermal conductivity of air, BTU/hr-ft^2-\(^0\text{R/ft} \)

k_p - Coefficient of thermal conductivity of pebbles, BTU/hr-ft^2-\(^0\text{R/ft} \)

l - Axial distance through pebble bed, feet

M - Mach number, dimensionless

N - Shape factor of heat storage material, \( N = 3 \) for spheres, dimensionless

P_t - Tunnel stagnation pressure, psia
NOMENCLATURE (cont)

\( P_r \) - Prandtl number, \( P_r = \frac{c_p \mu}{k/3600} \), dimensionless

\( \frac{dp}{dL} \) - Pressure drop per unit length of pebble bed, \( \text{lb/ft}^3 \)

\( R, r \) - Circular coverage function, dimensionless

\( Re_1 \) - Reynolds number in pebble bed based on pebble diameter, \( Re_1 = \frac{\rho V_d}{\mu} \), dimensionless

\( Re_2 \) - Reynolds number in pebble bed based on pebble surface area per unit volume,

\[ Re_2 = \frac{\rho U}{\mu S} \], dimensionless

\( S \) - Area of pebble surface per unit volume of pebble bed, \( \text{1/ft} \)

\( t \) - Time from beginning of cooling cycle, seconds

\( T_t \) - Tunnel stagnation temperature, \( ^\circ\text{R} \)

\( T_a \) - Transient air temperature, \( ^\circ\text{R} \)

\( T_{a_1} \) - Inlet air temperature, \( ^\circ\text{R} \) (\( T_{a_1} = 580^\circ\text{R} \))

\( T_p \) - Transient pebble temperature, \( ^\circ\text{R} \)

\( T_{p_1} \) - Initial pebble temperature, \( ^\circ\text{R} \)

\( U \) - Apparent fluid velocity based on \( A \) (no pebbles) ft/sec

\( V \) - Apparent fluid velocity based on flow area \( (A_e) \) in bed, ft/sec

\( w \) - Air flow rate through bed, lb/sec

\( x \) - Pebble-bed position parameter,

\[ x = \frac{Ha t}{c_p (\rho V A_e) 3600} \], dimensionless

\( \gamma \) - Specific heat ratio, dimensionless
NOMENCLATURE (cont)

$\theta$ - Run-time parameter, $= \frac{2NHt}{\rho_p cd 3600}$, dimensionless

$\mu$ - Fluid viscosity in bed, lb/ft sec

$\rho_b$ - Bulk density of pebble bed, $\rho_b = (1-e) \rho_p$, lb/ft$^3$

$\rho_p$ - Density of pebble material, lb/ft$^3$

$\rho$ - Fluid density in bed, lb/ft$^3$
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SUMMARY

This memorandum presents the predicted performance of the final design configuration of a pebble-bed-storage heater to be used with an intermittent, hypersonic wind tunnel. The pressure drop and the time-temperature variation of the air and the pebbles in the bed have been computed for all combinations of maximum and minimum design stagnation pressure and temperature for each test section Mach number.

The results indicate that at Mach 4 operation the tunnel stagnation pressure will be limited by bed fluidization. At all other Mach numbers, the pressure drop will not be sufficient to result in bed fluidization.

The calculated drop in air temperature at the heater outlet is insignificant for the anticipated tunnel-run times.
ANALYSIS OF PRESSURE DROP AND HEAT TRANSFER OF A PEBBLE-BED-STORAGE HEATER FOR A HYPERSONIC WIND TUNNEL

Introduction

An 18-inch-diameter test section, intermittent hypersonic wind tunnel is being installed at Sandia Corporation. The facility is scheduled to become operational in mid-1961. A 5-inch-diameter test section pilot model has been in operation since January 1960.

To avoid liquefaction phenomena when expanding air to Mach numbers approximately 5 or greater, it is necessary to increase the initial air temperature above ambient levels. The temperature required to avoid liquefaction is a function of the initial air pressure and the Mach number. Thus, operation of a hypersonic wind tunnel (with air as the test medium) requires preheating the air prior to its expansion in the nozzle. In addition, simulation of aerodynamic heating requires preheating the air; the selected 300°F maximum temperature will provide aerodynamic heating simulation at flight speeds up to approximately \( M = 6 \). A gas-fired, alumina, pebble-bed heater was selected for economy reasons and because the design and fabrication were within the "state of the art."

Extensive calculations of pressure drop and temperature decay were undertaken during the design of the heater. This paper presents the results of these calculations and discusses the tunnel facility and the heater operation.

Discussion

Description of Hypersonic Facility

The Sandia hypersonic wind tunnel is a blowdown-to-vacuum type with an 18-inch-diameter test section designed to operate over the Mach number range of 4 to 11. Figure 1 shows an elevation view of the tunnel. The tunnel drive consists of a 300 psig, 5200 ft\(^3\) air storage system and a 30,000 ft\(^3\) vacuum storage initially evacuated to 0.1 psia. The first vacuum tank (10,000 ft\(^3\)) is filled with 147,000 one-quart cans (49,250 pounds) to aftercool the tunnel exhaust and increase the run time.

Five nozzle assemblies (\( M = 4, 5, 7, 9, \) and 11), consisting of an integral settling chamber, nozzle, and test section with fused-quartz schlieren windows, will be mounted in a revolver mechanism for quick interchangeability. When the desired nozzle has been rotated into position, automatic clamps at the upstream and downstream ends secure it into the circuit.

The pitching strut section consists of a water-cooled sector with provision for electrical leads, pressure tubing, and water-cooling lines. Top and bottom wells in this section allow the sector to cover an angle-of-attack range of -10 to +20 degrees. The system is hydraulically actuated with a variable pitching rate of 2 to 6 degrees per second for force tests, and a pitch-pause capability for pressure tests.
Figure 1. Eighteen-Inch Hypersonic Wind Tunnel
A single fixed axisymmetric supersonic diffuser of converging-straight-diverging configuration will be used with the five nozzle assemblies. A bellows section downstream of the diffuser allows the pitching strut and diffuser section to be retracted a distance of 4.5 feet to provide access to models.

Tunnel operation is controlled by a pressure regulator valve and a quick-opening ball valve upstream of the heater, and a 16-inch slide valve at the heater outlet. With the ball valve and slide valve closed, the heater is prepressurized to the desired operating pressure. The run is initiated by opening the ball valve and slide valve simultaneously. An electropneumatic pressure control system senses the settling chamber pressure and adjusts the regulator valve to maintain this pressure at the desired level. A tabulation of the tunnel operating conditions is presented in Table I.

**Heater Description and Operating Mode**

A cutaway elevation of the pebble-bed heater is shown in Figure 2. The heater is approximately 90 inches in diameter and 18 feet high. The pebble bed, consisting of approximately 24,000 pounds of 1-inch-diameter alumina pebbles, is 62 inches in diameter and 7 feet high. Three courses of refractory brick, each 4.5 inches thick, are used for insulation in the cylindrical portion, while castable refractory is used in the upper and lower domes. Provision has been made for insertion of eight thermocouples in the bed; two at each of four levels. A drain through the lower dome is provided for removing the water which condenses from the combustion gases during initial warmup. A viewing port in the upper dome of the heater permits the operator to remotely monitor the pebble bed during operation via a closed circuit television system.

The selection of pebble size is dictated by bed pressure drop, bed heat transfer, and thermal shock considerations. Increasing the pebble size reduces the pressure drop but results in a degradation of the heat transfer and thermal shock characteristics. The selection of one-inch-diameter pebbles resulted from a compromise of pressure drop, heat transfer, and thermal shock characteristics.

An evaluation of the thermal shock characteristics of various sizes of pebbles was conducted by the Sandia Corporation Materials Laboratory (Reference 1). The properties of the pebbles tested are given in Table II. The results of this study are shown in Figure 3. As indicated in the figure, these thermal shock data correlate fairly well with the analysis of Crandall and Ging (Reference 2). The cold air (80°F) from the pressure storage tanks entering the heater inlet (Figure 2) during the blow cycle subjects the 1800°F pebbles to thermal shock; this operating regime is presented in Figure 3. However, since the operating conditions are well below the critical temperature curve, the pebbles should not fail as a result of thermal shock.

Heater operation consists of a heating cycle and a tunnel run (cooling) cycle. During the heating cycle, the pebble temperature is raised to the desired level by combustion gases (from the burner located in the top dome) passing downward through the bed and exhausting through the perforated pipe and exhaust stack to atmosphere. The natural gas burner is sized for a maximum capacity of $1.75 \times 10^6$ BTU/hrs with a turndown ratio of 5 to 1. In addition, control of combustion gas temperature is provided through addition of up to 600 percent excess air. The burner system incorporates an automatic control system which allows the burner to be operated unattended. A purge period before ignition removes any explosive vapors from the heater. Main burner ignition is provided by a pilot flame. Electronic circuitry insures that a satisfactory pilot flame exists before the main burner is turned on.
### TABLE I

Design Operating Conditions for the Tunnel

<table>
<thead>
<tr>
<th>Mach No.</th>
<th>Stagnation temperature (°F)</th>
<th>Stagnation pressure (psia)</th>
<th>Mass flow rate (lbs/sec)</th>
<th>Test section unit Reynolds No. (Re/ft x 10^-6)</th>
<th>Maximum run time (sec)</th>
<th>Test section static pressure (psia)</th>
<th>Test section dynamic pressure (psia)</th>
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<td>72.5</td>
<td>4.8</td>
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<td>275</td>
<td>200</td>
<td>275</td>
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</table>

### TABLE II

Properties of Coor's AD-94 94% Al₂O₃ Alumina Pebbles

- Pebble shape: Spherical
- Pebble size, dₚ: 1" diameter
- Pebble material density ρₚ: 225 lb/ft³
- Porosity: Gas-tight
- Color: White
- Working temperature, maximum: 3100°F
Figure 2. Ninety-inch-Diameter Pebble-Bed Heater
Figure 3. Thermal Shock Characteristics of Coor's AD-94 Pebbles
The heater is designed for operation to a maximum temperature of 2540°F (3000°F). However, the Haynes alloy perforated tube in the bottom of the bed is restricted to a maximum temperature of 1800°F. When operating at temperatures over 1800°F, the upper half of the bed will be fired to the desired temperature, with a gradient existing over the lower half to protect the perforated tube. Bed temperature, sensed by one of the thermocouples, is maintained at the desired level through automatic control of burner operation.

During the cooling cycle (tunnel run), the air and gas lines to the burner are isolated by interlocked valves. Dry air from the pressure storage enters through the perforated tube, passes upward through the pebble bed, and out through the 16-inch-diameter side exit and through the slide valve to the tunnel settling chamber.

**Heater Pressure Drop Analysis**

A correlation of experimental data for fluid flow through randomly packed granular beds has been presented by Carman (Reference 3). He presents an empirical relation, relating a nondimensional pressure drop parameter to the Reynolds number, based on particle surface area per unit volume. Bloom (Reference 4) presents a design analysis for a pebble-bed heater using this relation for which he suggests an accuracy of 35 percent. A subsequent experimental correlation of this equation was performed by Randall and Millwright (Reference 5), who reported that the measured pressure drop was 15 to 18 percent higher than calculated. They also determined the pressure drop at which lifting of a gravity-restrained pebble bed occurred. Initial pebble lifting occurred when the average unit length pressure drop became equal to 85 percent of the bed bulk density.*

Carman's equation for the pressure drop through granular beds may be expressed in the following form

\[
\frac{dp}{dL} = 2.4 \left( \frac{Re}{e} \right)^{0.1} \left( \frac{1-e}{e} \right) \frac{w^2}{\rho g d (de)^2}
\]  

Equation 1

The unit length pressure drop varies inversely with fluid density in the bed. The density will be minimum near the top of the bed where the fluid has attained maximum temperature and minimum pressure. Thus, the maximum unit length pressure drop occurs at the top of the bed.

Equation 1 has been used to calculate the pressure drop based on a density corresponding to tunnel stagnation pressure and temperature. Thus, the calculated value should correspond to the unit length pressure drop at the top of the pebble bed. Values have been calculated for maximum and minimum stagnation pressure and temperature at Mach numbers of 4, 5, 7, 9, and 11. Since the limiting design value of pressure drop is a function of bed bulk density, the data have been presented as the nondimensional ratio of

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*Preliminary information from recent tests in the Sandia Corporation pilot hypersonic wind tunnel indicate this figure is somewhat conservative. These data are to be published later.
pressure drop to bed bulk density plotted versus stagnation pressure with stagnation temperature as a
parameter. The data for test Mach numbers 4, 5, and 7 are presented in Figure 4; the Mach 9 and 11
values are insignificant and are not presented. Figure 4 indicates that the pressure drop varies linearly
with stagnation pressure. This assumption of linearity neglects the effect of pressure on Reynolds number.
The Reynolds number effect on pressure drop is very slight, however, since it appears to the -0.1 power.

It is apparent from the plots that only at Mach 4 operation is there danger of lifting the pebbles. At
Mach 4 operation, stagnation pressure will be limited to approximately 140 psia by bed fluidization. This
should be slightly conservative since the pebble-lifting point is based on average bed unit length pressure
drop while the pressure drop plotted is the maximum unit length value for the top of the bed. Initial opera-
tion at this level should be approached cautiously, however, because, as pointed out, the equation may
predict slightly low values for pressure drop.

Analysis of the Pebble-Bed Heat Transfer Characteristics

The temperature decay in a pebble-bed heater has been analyzed by Liu and co-workers (Reference 6)
who expressed the general heat transfer problem as a Bessel function integral equation. The expressions
derived by Liu, et al, for the variation of air and pebble temperatures in the pebble bed are, respectively:

\[
\frac{T_a - T_{a1}}{T_{p1} - T_{a1}} = \int_0^x e^{-(\theta x)} J_0(2\sqrt{\theta x}) \, dx
\]  

(2)

\[
\frac{T_{p1} - T_p}{T_{p1} - T_{a1}} = \int_0^\theta e^{-(\theta + x)} J_0(2\sqrt{\theta x}) \, d\theta
\]  

(3)

where x and \( \theta \) are dimensionless position and time parameters, respectively. This solution is based on
the assumptions that at time \( t = 0 \) the pebble temperature \( T_{p1} \) is uniform throughout the bed and that the
incoming air temperature \( T_{a1} \) is invariant with time.

Solutions of this set of equations for a large range of variables have been published by Steck (Ref-
ERENCE 7). The use of Steck's tabular solution reduces the above integral equations to the following algebraic
expressions:

\[
\frac{T_a - T_{a1}}{T_{p1} - T_{a1}} = f(R - r, r)
\]  

(4)

\[
\frac{T_{p1} - T_p}{T_{p1} - T_{a1}} = f(r - R, R)
\]  

(5)

20
Figure 4. Predicted Pressure Drop of the Pebble-Bed Heater
where $R$ and $r$ are defined as follows:

\begin{align*}
R &= \sqrt{2x} \\
r &= \sqrt{2\theta}
\end{align*}

The choice of time parameters was governed by anticipated run times, while position parameters were chosen to correspond to thermocouple mounting stations in the heater.

Physical and thermal properties of the Coor's AD-94 alumina pebbles are presented in Table II and Figure 5. Values corresponding to average bed temperature have been used in the calculations.

Pebble and air temperatures through the bed, with time a parameter, are presented in Figures 6 through 10 for Mach numbers 4 through 11, respectively. Figures 6A and 6B show pebble and air temperature profiles for the maximum and the minimum stagnation pressures associated with Mach 4 operation. It is evident that the maximum stagnation pressure operating condition, with its higher mass flow, is the more severe condition. Figures 7, 8, 9, and 10 present temperature profiles for Mach 5, 7, 9, and 11 maximum temperature, maximum pressure operating conditions, respectively.

As stated previously, a temperature profile will be established in the lower half of the bed during firing, to prevent overheating the perforated tube during maximum temperature operation at Mach 5 and above. This is not consistent with the assumption of a uniform temperature profile through the bed at time $t = 0$ required by the equations. However, the calculations indicate that a pebble temperature profile develops with time during the blow. At some time, $t'$, the computed temperature profile is such that the pebble-heat capacity is the same as in a pebble bed with an initial temperature gradient. For maximum temperature, Mach 5 operation the calculations have been carried out to times in excess of $t'$ plus the maximum expected run time. The results indicate that the air temperature leaving the bed will not be greatly affected by the initial gradient in the lower portion of the bed. For the higher Mach number operating conditions, the length of bed required for the air temperature to attain its maximum value is less than the length of bed initially at a uniform temperature. Therefore, at all operating conditions, the change in air temperature leaving the pebble bed should be negligible for the maximum run times listed in Table I.

Conclusions

1. During Mach 4 operation, the maximum stagnation pressure is limited to approximately 140 psia by bed fluidization. At all other Mach numbers, the pressure drop is not sufficient to cause bed fluidization.

2. The decrease in air temperature leaving the bed is insignificant for anticipated run times at all operating conditions.
Figure 5. Thermal Properties of Coor's AD-94 Alumina
Figure 6a. Variation of Air and Pebble Temperature with Time and Heater Station for Mach 4 Operation
Figure 6b. Variation of Air and Pebble Temperature with Time and Heater Station for Mach 4 Operation
Figure 7. Variation of Air and Pebble Temperature with Time and Heater Station for Mach 5 Operation

MACH 5 NOZZLE

\[ T_t = 3000 \, ^\circ R \]

\[ P_t = 210 \, ^\circ R \]

RUN TIME \( \approx 50 \, \text{SECS} \)
Figure 8. Variation of Air and Pebble Temperature with Time and Heater Station for Mach 7 Operation

MACH 7 NOZZLE
$T_t = 3000 \, ^\circ R$
$P_t = 250 \, $PSIA
RUN TIME $\approx 75$ SECS

---

PEBBLE TEMPERATURE
AIR TEMPERATURE

TIME $t = 75.2$ SECS
$\square \, t = 117.6$ SECS
$\triangle \, t = 169.4$ SECS
Figure 9. Variation of Air and Pebble Temperature with Time and Heater Station for Mach 9 Operation
Figure 10. Variation of Air and Pebble Temperature with Time and Heater Station for Mach 11 Operation

MACH 11 NOZZLE

\[ T_t = 3000 \, ^\circ R \]
\[ P_t = 275 \, \text{PSIA} \]

RUN TIME \( \approx 90 \, \text{SECS} \)

\[ \text{TIME} \ t = 67.8 \, \text{SECS} \]
\[ \text{TIME} \ t = 207.9 \, \text{SECS} \]
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