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Technical Notes

TECHNICAL NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes cannot exceed 6 manuscript pages and 3 figures; a page of text may be substituted for a figure and vice versa. After informal review by the editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Cored Brick Storage Heater Analysis

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Introduction

THE problem of heat transfer from a gas stream to a bed consisting of chunks of solid materials has been addressed by chemical engineers.[1] Their results have been used in the design of storage heaters for intermittent hypersonic wind tunnels.[2] Some of the earliest storage heaters consisted of beds of round pebbles in a thermally insulated pressure vessel. The pebbles were preheated to some desired temperature, usually by a hot gas such as combustion products.

Later storage heaters used as a heat source cored bricks that, when stacked, presented a cluster of cylindrical passages through which the gas to be heated, usually air, flowed. The advantage of cored bricks is their rigidity as compared with the motion of pebbles relative to each other as they are heated and cooled down, or simply disturbed by the passage of air through them. The rubbing of the pebbles results in spalling, which adds unwanted impurities to the air. Thus, cored bricks provide a cleaner heat source.

While analyses exist for the calculation of the temperature–time history of a gas passing through a porous medium,[3] or a bed of broken solids[1] applicable to a pebble bed, no report was found in the open literature for a cored brick heater. The general heat transfer equations are similar for the two types of heater, so that the numerical results of these earlier studies can be directly applied to the cored brick by using the appropriate variables given in the present analysis, an abbreviated version of Ref. 4.

Heater Transfer from Solid to Gas

Heater Configuration

The heater consists of layers of cored bricks inside a thermally insulated pressure vessel. These layers are aligned so that, in cross section, there are rows of holes in the form of circular cylinders extending from one end of the heater to the other, through which the gas to be heated will pass. The porosity η is the ratio of the area represented by the holes, to the cross-sectional area of the heat storage bed A. Thus, the cross-sectional area of solid would be $A(1 - \eta)$ and that of the holes would be $A\eta$.

Assumptions

Several simplifying assumptions are made, some of which are in conformity with the earlier studies, as follows:

1) The holes are so densely spaced and the brick material has such a high thermal diffusivity that the brick temperature is uniform at each cross section.
2) The transfer of heat in the brick or gas is negligible compared with the transfer of heat from the brick to the gas.
3) The rate of heat transfer from solid to gas at any point is proportional to the temperature difference between solid and gas at that point.
4) The thermal properties of the gas are constant, independent of temperature.
5) The pressure drop of the gas across the heater is negligible.
6) The flow of gas in the holes is assumed to be well subsonic so that an incompressible flow analysis can be used.
7) Reynolds number variations across the heater are neglected.

Pipe Flow

The geometry is such that the heat transfer relations for the gas can be obtained from classical pipe flow. The rate of heat transfer per unit area at the interface from solid to gas is given by

$$q_0 = St\rho U c_p(\theta - T) \tag{1}$$

where St is the Stanton number or heat transfer coefficient, ρ is the density of the gas, U is the average velocity of the flow in the pipe, c_p is the specific heat of the gas at constant pressure, $\theta = \theta(x, t)$ is the temperature of the solid, and $T = T(x, t)$ is the temperature of the gas, where x is the axial distance from the inlet of the cored brick bed, and t is the time from the moment gas enters the bed. For most cases of interest, flow in the hole (pipe) is turbulent as Reynolds numbers based on pipe diameter are considerably larger than the critical value of about 2.3×10^3, given by Schlichting.[5] From Reynolds analogy, the St is related to the skin friction coefficient for turbulent flow as follows:

$$St = C_f/(2Pr^{2/3}) \tag{2}$$

where Pr is the Prandtl number

For air at standard temperature, $Pr = 0.73$. We will take this value in Eq. (2), yielding

$$St = 0.62C_f \tag{3}$$

For incompressible turbulent pipe flow, Schlichting[5] gives the following relations for the skin friction coefficient:

$$C_f = 0.0791Re_d^{-1/4} \qquad Re_d < 10^5 \tag{4a}$$

$$C_f^{-1/2} = 4\log_{10}(Re_d C_f^{1/2}) - 0.396 \qquad Re_d > 10^5 \tag{4b}$$

where d is the diameter of the pipe, and Re_d is the Reynolds number based on pipe diameter ($Re_d = \rho Ud/\mu$).

For cases in which Re_d is less than 10^5, Eqs. (3) and (4a) give the simple result for the St:

$$St = 0.049Re_d^{-1/4} \tag{5}$$

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The values of C_f obtained by Eqs. (4a) and (4b) differ by less than 20% at Re as high as 10^6, so that one can consider using this much simpler formula for a preliminary design, even for values of Re_d well in excess of 10^5.

Heat Flow Analysis

The rate of heat flow from solid to gas per unit depth of a hole is given by [see Eq. (1)]

$$\pi dq_0 = St\pi d\rho Uc_p(\theta - T) \tag{6}$$

This represents the rate of heat given up by the solid in the neighborhood of a hole. Since the cross-sectional area of a hole is $\pi/4d^2$, and the porosity is η, referring to the Heater Configuration section, the cross section of solid giving up heat to a single hole is $\pi/4d^2(1 - \eta)/\eta$. Thus, the rate of heat per unit depth given up by the solid at a particular location x and time t, is

$$\frac{\pi}{4} d^2 \frac{(1 - \eta)}{\eta} \rho_b c_b \frac{\delta\theta}{\delta t} = St\pi d\rho Uc_p(T - \theta)$$

or

$$\frac{\delta\theta}{\delta t} = 4St\rho Uc_p \frac{\eta}{[d(1 - \eta)\rho_b c_b]}(T - \theta) \tag{7}$$

where ρ_b is the density of the solid, and c_b is its specific heat. Now, the mass flow of gas is

$$\dot{m} = A\eta\rho U \tag{8}$$

Since $\dot{m}$ is constant during an operation, it follows that ρU is constant. St is also assumed constant as Re variations are neglected. Thus, Eq. (7) can be written as

$$\frac{\delta\theta}{\delta t} = K_b(T - \theta) \tag{9}$$

where the constant $K_b = 4St\dot{m}c_p/[dA(1 - \eta)\rho_b c_b]$.

The heat per unit depth absorbed by the gas in a given hole as it passes a particular location x at time t, is

$$\frac{\pi}{4} d^2 \rho c_p \frac{DT}{Dt} = St\pi d\rho Uc_p(\theta - T)$$

or

$$\frac{DT}{Dt} = \frac{\delta T}{\delta t} + U\frac{\delta T}{\delta x} = 4St\frac{U}{d}(\theta - T) \tag{10}$$

The first term on the left-hand side (LHS), the local rate of heat addition caused by the unsteadiness of the flow, is small compared with the second term, the rate of heat addition caused by convection or displacement of the flow in the tube. Hence, the first term on the LHS will be neglected, reducing Eq. (10) to

$$\frac{\delta T}{\delta x} = K_g(\theta - T) \tag{11}$$

where the constant $K_g = 4St/d$. In these equations it is convenient to use Eq. (5) for St.

References 1 and 3 introduce the nondimensional variables Y and Z (In Ref. 3 the variable is given as $Z = K_b(t - x/U)$; however, as noted in Ref. 1, for gas flows $t >> x/U$, and so the latter term may be neglected.) For the present case, the Y and Z variables have the values

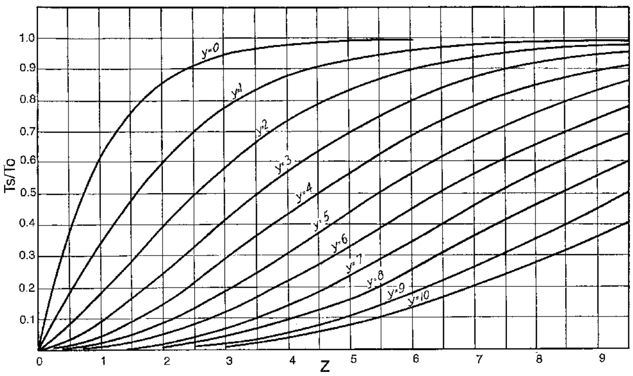

Fig. 1 Temperature–time history of solid for values of Y from 0 to 10 (Ref. 3).

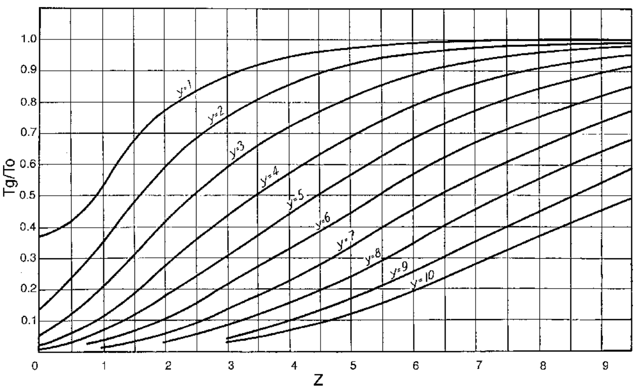

Fig. 2 Temperature–time history of gas for values of Y from 1 to 10 (Ref. 3).

$$Y = K_g x \qquad Z = K_b t \tag{12}$$

They present solutions to Eqs. (9) and (11) in the form of graphs that give the ratio of solid T_s and gas T_g temperatures to the initial gas temperature T_0 as functions of Y and Z. In the cases they consider, a hot gas moves through a cold bed of solid particles. In the present case, a cold gas moves through a hot bed of solid material. Their results are related to the present case as follows.[2]

If T_{in} is the inlet temperature of the gas, and θ_0 is the initial temperature of the cored brick bed, then

$$(T - T_{in})/(\theta_0 - T_{in}) = 1 - T_g/T_0(Y, Z) \tag{13a}$$

$$(\theta - T_{in})/(\theta_0 - T_{in}) = 1 - T_s/T_0(Y, Z) \tag{13b}$$

T_g/T_0 and T_s/T_0 are functions that involve infinite series of modified Bessel functions of the first kind. Numerical values of T_g/T_0 and T_s/T_0 are given in Ref. 3 for values of Y and Z from 0 to 10 (shown graphically in Figs. 1 and 2), and in Ref. 1 for values of Y and Z up to 500.

In summary, the present analysis enables one to use the numerical values of Refs. 1 and 3 by providing the variables appropriate to a cored brick storage heater.

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Operation of Quasi-Two-Dimensional Projectiles in a Ram Accelerator

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Introduction

THE ram accelerator is a novel launcher concept that accelerates a supersonic projectile in a tube filled with combustible gas.[1,2] Shock waves around the projectile ignite the gas, and combustion supports a high-pressure region on the base of the projectile. Several propulsive modes have been proposed and investigated experimentally, theoretically, and numerically. Most experimental work to date has been done on the thermally choked mode, where the projectile is below the Chapman–Jouguet (CJ) detonation speed of the mixture.[3]

In prior experiments, most projectiles were designed with a nose cone attached to a truncated conical base. Figure 1 shows a typical projectile used in the University of Washington (UW) ram accelerator facility. The fins are required to center the projectile as it travels down the tube. Other ram accelerator facilities have used rails on the tube wall to guide an axisymmetric projectile.[4] The fins and rails obscure the flowfield around the projectile, making optical and spectroscopic diagnostics difficult. Visualization techniques are further complicated by the curved tube wall.

A two-dimensional ram accelerator without fins or rails obstructing the flow over the projectile would greatly assist investigation of the complex flowfield, as well as simplify the geometry for computational modeling. This has motivated the construction of a two-dimensional ram accelerator with a rectangular bore at Hiroshima University (HU) in Japan.[5] The projectile and tube cross section of this facility are shown in Fig. 1 (not to scale). Lacking fins, the projectile is guided by rails on the tube wall, allowing pure two-dimensional flow over the projectile. Windows on the tube side walls provide convenient access for flow visualization.

The feasibility of ram acceleration in a two-dimensional geometry is the subject of this Note. A quasi-two-dimensional (Q2D) projectile was designed that can be used in a conventional ram accelerator with a circular cross section (Fig. 1). This paper reports the results of experiments using this Q2D projectile in the UW ram accelerator.

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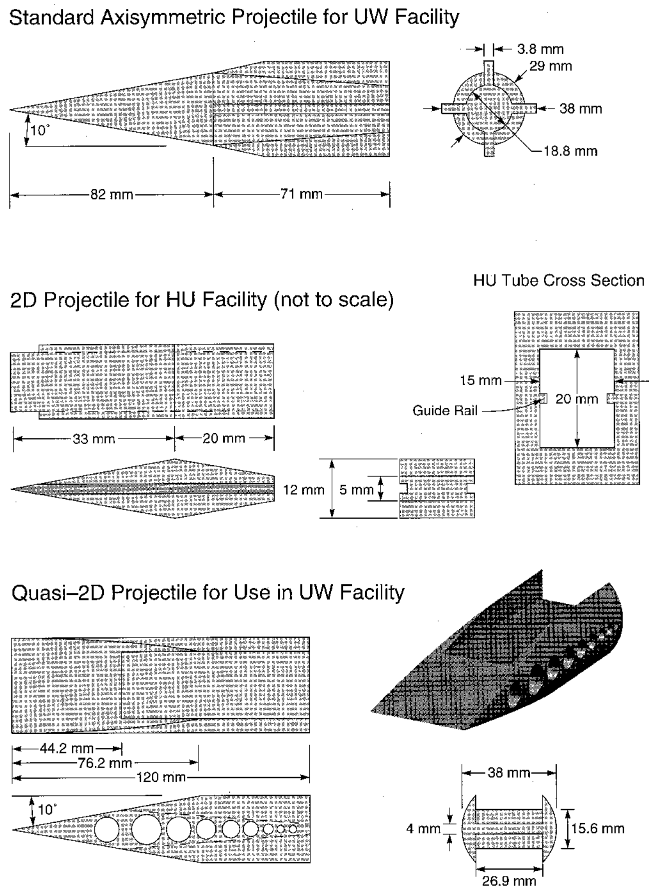

Fig. 1 Axisymmetric projectile for use in the UW facility, two-dimensional projectile for use in the HU facility, and Q2D projectile for use in the UW facility.

Experimental Facility and Procedure

The facility used in these experiments is the 38-mm bore, 16-m-long ram accelerator at the UW. A helium gas gun launches the projectile into the test section at supersonic velocity. The combustible gas mixture is contained in the test section by diaphragms at each end. Electromagnetic sensors, for tracking a magnet carried onboard the projectile, and pressure transducers, for monitoring wave activity at the tube wall, are mounted at 40-cm intervals along the test section.

The Q2D projectile shown in Fig. 1 was fabricated from aluminum alloy. The throat to tube area ratio is 0.4. Holes through the projectile are used to reduce the mass to 87.6 g. The curved extensions on the rear half of the projectile contact half the circumference of the tube and act to stabilize the projectile. The projectile was launched from the helium gas gun with a conventional perforated polycarbonate obturator.[6] The obturator required reinforcement with a 1.7-mm perforated aluminum alloy face plate to prevent it from breaking on the base of the Q2D projectile when accelerated by the gas gun.

Experimental Results and Discussions

Diffuser Starting in Inert Gas

As a preliminary experiment, the Q2D projectile shown in Fig. 1 was fired into the test section filled with pure nitrogen at 25 atm to evaluate the diffuser performance. The result is shown in Fig. 2. The entrance velocity was 1180 m/s, equivalent to a Mach number of $M = 3.3$ in nitrogen. The diffuser properly started, meaning supersonic flow was established past the projectile throat. Because of friction and aerodynamic drag, the projectile gradually decelerated in the first 8 m of the test section. At this point, when the projectile velocity had decreased to 910 m/s ($M = 2.6$), the flow around the projectile