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Transient High Speed Gas Flow in a Gravel Stemming Column

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Summary

Transient high speed gas flow up a gravel stemming column is investigated. The results provide an upper bound to the extent of gas pressure propagation in the first several seconds following an underground nuclear test. Application of these results to the LASL BANDICOOT event demonstrate that gas flow through the gravel column cannot explain that vent.

Introduction

It has recently been proposed that the BANDICOOT vent could possibly be attributed to sudden gas flow up the gravel stemming column [1].* In this scenario, gas rapidly rises to within 15 m of the surface where it is stopped by a fines plug and subsequently ruptures the liner. As the working point was 220 m beneath the fines plug and the vent commenced 5 s after detonation, it is possible to test this conjecture analytically.

To determine whether gas can flow this rapidly through a gravel bed, similarity analysis of high speed flow through packed beds [2] is employed. Condensation of cavity gas would retard pressure propagation [3,4] but is neglected here. Instead, we will simply examine ideal gas flow.

Analysis

In order to first determine the flow regime encountered should gas rise through the bed this rapidly, a Reynolds number based on gravel diameter is estimated. Air, with a kinematic viscosity of about $16 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$ flowing a couple hundred metres through 6.4 mm (1/4 in.) gravel in 5 s will have a Reynolds number of order 10^4 . At such Reynolds

*Numbers in brackets denote entries in References.

numbers, inertial effects are significant as gas flows through the tortuous paths about the gravel. Darcy's law, which neglects inertial effects, is not valid. Instead, Forchheimer's [5] relation describes the flow resistance. In one dimension, this is

$$u + b\rho |u|u = - \frac{k}{\mu} \frac{\partial p}{\partial x} \quad (1)$$

u is the apparent fluid velocity. ρ , μ and p are its density, viscosity and pressure. The permeability of the bed is denoted by k . x is the position coordinate along the bed. The empirical coefficient b may be estimated using Ergun's [6] expression

$$b = \frac{d}{85.7 \mu (1-\epsilon)} \quad (2)$$

ϵ is the porosity of the bed. The permeability of a monodisperse bed is given by the empirical relation [7]

$$k = 6.54 \times 10^{-9} d^2 \quad (3)$$

At the high Reynolds numbers of interest here, the linear drag provided by the leading term of equation (1) can be neglected leaving

$$b\rho |u|u = - \frac{k}{\mu} \frac{\partial p}{\partial x} \quad (4)$$

This relation, together with the continuity equation

$$\epsilon \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x} (\rho u) = 0 \quad (5)$$

and the ideal gas equation of state

$$p = \rho RT \quad (6)$$

combine to produce

$$\epsilon \frac{\partial p}{\partial t} + \frac{\partial}{\partial x} \left(- \frac{k p}{RT u} \frac{\partial p}{\partial x} \right)^{1/2} = 0 \quad (7)$$

R is the gas constant and T is the gas temperature, which is taken to be constant since it will be equal to the bed temperature over the bulk of the bed.

$$P = (p - p_0) / (p_1 - p_0) \quad (8)$$

p_0 is the initial pressure throughout the bed, p_1 is a constant pressure suddenly applied at the lower bed surface where x is zero.

The flow in a finite column is the same as the flow in a semi-infinite column until such time as the pressure changes become significant near the distant boundary. For short times, then, the flow in the gravel bed is governed by equation (7) subject to

$$\begin{aligned} P &= 0 \text{ at } t = 0 \\ P &= 1 \text{ at } x = 0 \\ P &\rightarrow 0 \text{ as } x \rightarrow \infty \end{aligned} \quad (9)$$

Under these conditions, it has been demonstrated [2] that the solution to equation (7) can be expressed as a function of a single variable.

$$\xi = x \left(\frac{\epsilon^2 h \mu}{k RT t^2} \right)^{1/3} \quad (10)$$

Further, equation (7) becomes the ordinary differential equation

$$\xi \frac{dp}{d\xi} - \frac{d}{d\xi} \left[\frac{-9}{8} \frac{d}{d\xi} \left(p^2 + \frac{2p}{N-1} \right) \right]^{1/2} = 0 \quad (11)$$

and the boundary conditions (9) are

$$\begin{aligned} p &= 1 \text{ at } \xi = 0 \\ p &\rightarrow 0 \text{ as } \xi \rightarrow \infty \end{aligned} \quad (12)$$

The solution for several values of N , (p_1/p_0) , is shown in Figure 1. Note that any high pressure ratio flow is well-represented by the infinite N curve.

To determine the pressure distribution for RANDICOOT at 5 s, we relate ξ to x using the values

$$\begin{aligned} R &= 0.287 \text{ kJ/kg K} \\ T &= 300 \text{ K} \\ d &= 6.4 \text{ mm (1/4 in.)} \\ \epsilon &= 0.35 \\ t &= 5 \text{ s} \end{aligned}$$

in equations (2), (3) and (10). We find

$$\xi = .062 \text{ m}^{-1} * x \quad (13)$$

Since, from Figure 1, the pressure has changed little at ξ equal to 3, the pressure is essentially ambient more than 48 m from the bottom of the bed. No high pressure could be generated beneath the fines plug by flow through gravel in this short time.

For the pressure distribution to propagate four times as far requires, according to equation (10), eight times as long. Even at 40 s, no high pressure could appear beneath the plug as a result of flow through porous media.

References

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FIGURE 1