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ScienceDirect
Applied Thermal Engineering 27 (2007) 1352–1362
APPLIED THERMAL ENGINEERING
www.elsevier.com/locate/apthermeng

Single-phase heat transfer in the high temperature multiple porous insulation

T.K. Lim *, B.P. Axcell, M.A. Cotton

School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Manchester M60 1QD, UK

Received 26 November 2005; accepted 17 October 2006
Available online 22 December 2006

Abstract

An experimental study of steady state flow and heat transfer has been conducted for the multiple plate porous insulation used in the reactor pressure vessels of 'Magnox' nuclear power stations. The insulation pack studied, consisting of seven dimpled stainless steel sheets and six plane stainless steel sheets, was of the type installed in the Sizewell A plant. A large scale experimental test facility, based on the guarded hot plate method, was used for measuring the effective thermal conductivity of Magnox reactor pressure vessel insulation, which consists of alternate layers of plain steel foil and dimpled foil. The measurements were made both with the fluid within the insulation pack nominally stationary and with an imposed flow through it, simulating leakage through the insulation pack. The experimental conditions corresponded to a heat flux of 75–1000 W/m^2, fluid pressures of atmospheric to 5 bar gauge, pack orientations in range of 0°–45° relative to the horizontal, leakage velocities ranging from 0.05 m/s to 0.20 m/s and inlet air bulk temperatures ranging from 18 °C to 290 °C. Local values of effective thermal conductivity of 0.04–0.23 W/m K were obtained for the above experimental conditions. The heat transfer modes in the insulation pack were conduction through the contacting metallic foils, thermal radiation across the gas gaps, and conduction and convection in the air. The effective thermal conductivity of the porous insulation increased with increasing air pressure, inclination angle, and air velocity. Buoyancy effects increased with increasing inclination angle and air pressure.

Keywords: Porous insulation; Laminar flow; Heat transfer; Guarded hot plate method

1. Introduction

The reactor pressure vessel (RPV) is the structural component of the most fundamental importance in a nuclear power plant. The RPV houses the radioactive nuclear fuel, which generates heat. It is one of the major concerns in the nuclear power industry to maintain the structural integrity of the RPV for safe operation of the plant. The RPV undergoes various loadings during normal plant operations, which include heat-up, cool-down, and pressure tests. Under these operations, the reactor coolant is subjected to temperature and pressure changes of moderate rate and amplitude, resulting in thermal stresses in the reactor vessel wall. A large number of these operations occur during the total life of the plant.

During transient operation at either start-up or shutdown, the reactor pressure vessel faces a large temperature difference, owing to the cold environment on the outside and the high heating of the core itself. In this case, a cracking problem might occur on the wall reactor because the crack driving force is proportional to the stress. The use of thermal insulation on the wall of the RPV allows the reactor pressure vessel to operate with coolant temperatures up to 370 °C whilst preventing the wall of the RPV from getting too hot. In addition, the thermal insulation employed in a gas-cooled reactor limits the temperature differences across the wall of the RPV, resulting in a smaller differential expansion and hence, less thermal stress in the wall of the RPV. Degradation of the insulation performance by leakage flow through the insulation pack may

* Corresponding author. Tel.: +44 6012 6073285; fax: +44 603 61570869.
E-mail address: easonlim2003@yahoo.com (T.K. Lim).

1359-4311/$ - see front matter
doi:10.1016/j.applthermaleng.2006.10.037

Nomenclature

A	cross section area of the insulation pack
A_{inlet}	cross section area of the injected flow
c_p	specific heat capacity of air
c_f	local friction coefficient $\left(\frac{\tau_w}{\frac{1}{2}\rho U_m^2}\right)$
f	wall friction coefficient, $\left(\left(\frac{H}{L}\right) \times (\Delta p_s) \times \left(\frac{2}{\rho u_{inlet}^2}\right)\right)$
g	acceleration due to gravity (9.80665 m/s^2)
H	thickness of insulation pack
k	thermal conductivity of air
k_{bp}	thermal conductivity of back plate
k_{cp}	thermal conductivity of cover plate
k_{eff}	effective thermal conductivity of insulation pack
k_r	thermal conductivity due to thermal radiation
k_s	thermal conductivity of metallic foil
L	length of the insulation pack
m	mass flow rate of the injected air ($\rho u_{inlet} A_{inlet}$)
Re	Reynolds number $\left(\frac{u\rho H}{\mu}\right)$
Δp_s	pressure difference across the insulation pack
Q_{MH}	power of main heater
$\sum Q_{loss}$	total lateral and axial losses
T	temperature
T_{air}	inlet air temperature
$T_{bp,m}$	average temperature of back plate
$T_{cp,m}$	average temperature of cover plate
$T_{inlet,m}$	average air bulk temperature at inlet section
$T_{outlet,m}$	average air bulk temperature at outlet section
ΔT	temperature difference of the injected air ($T_{inlet,m} - T_{outlet,m}$)
u_{inlet}	injected air velocity
x_{cp}	thickness of cover plate
x_{bp}	thickness of back plate

Greek letters

θ	angle of inclination
ρ	density of air $\left(\frac{p}{RT}\right)$

Subscripts

air	air
b	bulk
back plate	back plate (cold boundary)
cover plate	cover plate (hot boundary)
e	exit of the insulation pack
i	entrance of the insulation pack
inlet	air inlet temperature of the air heater
m	mean
w	wall

occur due to damage of structural members or incorrect installation during construction.

The main objective of these investigations, as a fundamental study for evaluating the performance of a type of porous insulation, was to examine experimentally heat transfer through the porous insulation used inside the reactor pressure vessels of the Sizewell A Magnox reactors. Semi-empirical studies of the performance of the fibrous insulation had been conducted by various researchers, for example [3,5,2]. However, the porous specimens investigated by the above researchers were different from this study. In this study, the insulation pack investigated was made from stainless steel instead of fibrous material.

The experiment adopted a guarded hot plate method to take experimental measurements of the effective thermal conductivity of the insulation pack under different operating conditions: a temperature difference across the insulation up to 120 K, temperature of cover plate (hot boundary) up to 300 °C, vessel pressures up to 5 bar gauge, and a heat flux up to 1000 W/m^2. In the experiments with leakage flows, the effects of air velocities of 0.05–0.2 m/s were examined.

Slifka et al. [6] made steady-state measurements of the thermal conductivity of Magnesium Oxide by using a one-sided guarded hot plate. Their experiments covered a temperature range from 400 K to 1300 K [7] used the heat flow meter apparatus for measuring the apparent thermal conductivity of high-density fibrous glass board. The measurements were conducted over temperatures in the range of 10–50 °C at atmospheric pressure. The heat flow meter apparatus utilised a single heat-flux transducer embedded in the centre of the hot-face surface. Another experimental approach is known as the flash diffusivity method, see [1]. In the flash diffusivity method, a short duration burst of energy, typically from a laser, heats the surface of a thin sample approximately 2 cm in diameter. The transient temperature at the rear surface of the sample is measured by using an infrared detector. The heat diffuses through the sample, leading to a temperature rise on the sample's rear surface. This method directly measures the thermal diffusivity of the sample. Thermal diffusivity is computed as [1]

$$\alpha = \frac{k}{\rho c} = 1.38\left(\frac{L^2}{\Pi^2 t_{\frac{1}{2}}}\right) \quad (1)$$

where L is the sample thickness and $t_{1/2}$ is the time required for the temperature at the back surface to reach one-half of its maximum.

2. General arrangement of porous insulation

Fig. 1 illustrates the arrangement of the Sizewell A insulation pack. The insulation pack comprises three staggered layers. In the first and second layers, there are two plane foils and two dimpled foils for each layer. Layer three consists of three dimpled foils and two plane layers. The