Experimental Thermal and Fluid Science 54 (2014) 151–157

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

An experimental investigation of convection heat transfer during filling of a composite-fibre pressure vessel at low Reynolds number

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ARTICLE INFO

Article history:
Received 20 July 2013
Received in revised form 31 January 2014
Accepted 1 February 2014
Available online 8 February 2014

Keywords:
Convection heat transfer correlation
Composite pressure vessel

ABSTRACT

The heat transfer process during filling of an evacuated vessel at low Reynolds number was investigated experimentally using air as the flow medium. The data was analysed using a thermodynamic model similar to one currently in use for the design of systems using commercial carbon fibre reinforced plastic vessels for storage of compressed hydrogen gas. Model assumptions included perfectly-stirred conditions within the vessel, one-dimensional unsteady heat conduction through the composite vessel wall, ideal gas and frictional adiabatic flow conditions through the inlet tube. A transition phenomenon from laminar to turbulent flow was observed by decreasing the inlet diameter while maintaining a similar mass flow rate. Based on the measurements, a new empirical correlation for the Nusselt number under low Reynolds number flow conditions is proposed.

1. Introduction

This study is part of a larger investigation to explore heat transfer processes that occur during pressurizing and depressurizing of gas containment vessels. The theme has particular importance for carbon fibre reinforce plastic vessels used in fuel cell vehicles which have problems with overheating during the semi-adiabatic compression process during filling [1–8]. Other applications include accidental depressurization where the concern may be excessive internal cooling of a metal container [9] and predictions of gas leakage rates from vessels [10]. For mobile applications, vessel sizes typically range from a few litres suitable for hydrogen powered scooters or bicycles [11] to banks of 200 litre vessels used in fuel cell buses [12]. For applications which require very small vessels, metal hydride hydrogen storage has been given relatively more attention than compressed storage in the literature based on the perception that it is safer [13]. Compressed gas storage is still the most popular choice for commercial hydrogen fuel cell cars.

When filling pressure vessels with compressed gas, flow work is done in the container which causes heating. In the case of carbon fibre reinforced plastic (CFRP) vessels it becomes particularly important to be able to predict the temperature rise since the material is sensitive to high temperatures. A number of studies have considered computational fluid dynamics (CFD) modelling [3–6] and experimentation where the temperature during filling was monitored [7,8]. Somewhat surprisingly, most research has focused on the temperature of the gas rather than the temperature distribution in the vessel wall and there appears to be a lack of fundamental data describing the heat transfer process. Very little attention has been given to heat transfer in this flow situation at low Reynolds number.

Recently, Winters et al. [14] experimentally and numerically investigated heat transfer during depressurization of a spherical vessel. They found good agreement between their results and an analytical model by Paolucci [15] during the early stages of gas expansion followed by a period of time where natural convection heat transfer dominated. Charton et al. [9] considered the flow of gas into an evacuated vessel connected to a pressurized vessel via a thin tube. Their experimental data was in reasonable agreement with predictions from a thermodynamic model which utilized a natural convection heat transfer correlation for both the supply vessel and the receiver. In their model, the correlation used for the Nusselt number was of the form $Nu = CRa^n$ where C is a constant and n is approximately 0.25 for laminar natural convection and 1/3 for turbulent natural convection [16,17]. Woodfield et al. [18], in their study on depressurizing and pressurizing of gas storage vessels, found that heat transfer during filling of the vessel was better described using a mixed convection heat transfer correlation

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http://dx.doi.org/10.1016/j.expthermflusci.2014.02.001

Nomenclature

a	thermal diffusivity
A	inside area of vessel
c	sound speed of air
c_s	specific heat for solid
C_p	constant pressure specific heat of gas
d	internal diameter of supply pipe
D	internal diameter of experimental vessel
g	acceleration due to gravity
H	internal height of vessel
h_a	specific internal enthalpy of supply
h_f	head loss due to friction in supply pipe
L	length of supply pipe
m	mass of gas in vessel
M	Mach number
$\dot{M}$	mass flow rate
Nu	Nusselt number
P	pressure in vessel
r	radial position in the wall
Ra	Rayleigh number
Re	Reynolds Number
R_{air}	ideal gas specific to air
R_{cyl}	internal radius of cylinder
R_{in}	inner radius
R_{out}	outer radius
t	time
t_w	thickness of vessel wall
T_a	supply temperature of gas
T_e	environment temperature
T_g	gas temperature
T_o	initial temperature of gas
T_s	temperature of solid
T_w	inside temperature of wall
u	specific internal energy
v	velocity in supply pipe
V	internal volume of vessel
V_f	volume fibre fraction
Greek	
α_e	convection heat transfer coefficient from outside wall to environment
α_h	convection heat transfer coefficient from gas to the wall
β	volumetric thermal expansion coefficient
λ	thermal conductivity
ν	Poisson's ratio
μ	dynamic viscosity
ρ	density
τ	Fourier number = $atR_{cyl}{}^{-2}$

involving both the inlet tube Reynolds number and the Rayleigh number. Their correlations captured most of their own data well but under-predicted the heat transfer during the very early stages of depressurizing of the vessel. In commercial applications it is common to assume that the heat transfer coefficient has a constant value for entire filling process [2].

Because of safety issues in the use of high-pressure hydrogen gas, we are seeking to develop low-pressure physical models suitable for exploring the details of the science of heat transfer within a confined pressurizing or depressurizing flow field. By developing such models, detailed experimental investigations can be carried out both safely and cost effectively. In this study we are using a small vessel that is initially evacuated and then filled with ambient air whilst simultaneously monitoring the temperatures in the flow field to elucidate the heat transfer process. This approach has an added merit that the ambient supply can be modelled accurately as an infinite source with a constant specific enthalpy. The conditions considered correspond to the low Reynolds number regime for this class of flow problems.

2. Design and construction of experimental vessel

Composite pressure vessels are often constructed using a filament winding technique (e.g. [19]). For our purpose, however, it is desirable to have the option of embedding thermocouples in the wall itself in between layers of fibre. To give us this flexibility we opted for a vacuum bag resin infusion technique, which we have available in our laboratory, for constructing the composite vessel. The experimental vessel was designed to support an internal vacuum, or 1 atmosphere of external pressure. The vessel was cylindrical in shape and had an internal radius of 0.035 m and an internal height of 0.180 m.

The composite vessel was constructed in four pieces – two cylindrical halves and two flat ends. Fig. 1 gives an illustration of the vessel with one of the cylindrical halves removed for clarity. This design was chosen to enable accurate positioning of the thermocouple junctions for measuring the gas temperature. Unidirectional carbon fibre with an area density of 200 g/m^2 was used in the construction. A mould was prepared from a half cylinder of mild steel, which had been machined to an external diameter of 70 mm. This was glued to a flat aluminium plate using a 2 part epoxy adhesive. The entire mould was coated with epoxy and cured for 4 h at 80 °C, before sanding to achieve a smooth finish. Endplates were cut from Perspex and clamped in place during construction. After laying up two layers of fabric, thermocouples were embedded into the wall. The constructed vessel wall had a total of twelve layers of fibre and a final thickness of 4.0 mm.

3. Experimental setup

Fig. 2 shows a schematic of the experimental setup. To monitor temperature history and determine heat transfer during the experiment, fourteen thermocouples were used with four inside the vessel wall, eight inside the gas (in the positions shown in Fig. 1), one measuring the ambient temperature and one measuring the temperature of the air inside the supply tube just before valve 1. The thermocouples in the wall were at the same vertical positions as those in the gas shown in Fig. 1. All thermocouples were connected to a multi-channel digital multimeter which itself was connected to a personal computer via a GPIB link. Flow into the vessel was controlled using a long supply tube (30 m in length) with a small diameter (1.59 mm internal diameter) (see Fig. 2). The internal diameter of the tube was measured gravimetrically by filling a long section of the tube with water which was subsequently measured and weighed.

The pipe connections were push-fit union type joints suitable for air and gas at low pressure. The vacuum pressure gauge shown in Fig. 2 was used to measure the initial and final pressures in the cylinder. The known geometry of the supply tube allowed for a well controlled and predictable flow of air into the vessel. The thermal camera was used to confirm the uniformity of the initial internal wall temperature distribution.