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MEASUREMENT AND SIMULATION OF LOW TEMPERATURE PACKED BED REGENERATORS

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EXTENDED ABSTRACT

The storage of thermal and electrical energy will become increasingly important with the transition to a low carbon economy. Packed bed regenerators (PBR) can be used to directly store thermal energy. When integrated in a cryogenic energy storage system, this can improve the round trip efficiency. In PBRs, a fluid is passed over a loosely packed solid material. This relative fluid motion is used to transfer thermal energy either to or from the solid phase. The solid and liquid used can vary greatly, depending on the application. Commercial PBRs are generally operated at elevated temperatures, with inlet temperatures ranging from 350 to 600 K (Cascetta et al. 2014).

The design of PBRs requires accurate material properties which can be used to evaluate the thermodynamic performance of the PBR, usually through simulation. Material properties, including specific heat and thermal conductivity, at ambient and elevated temperatures are well documented. However, there is limited published data for both material properties at low (<150 K) temperatures and the performance of a PBR operating at cryogenic temperatures. Future development of PBRs for this application will be limited without an understanding of the material properties at the requisite temperatures (down to -196°C for liquid nitrogen). If the material properties are unknown, assumptions must be made when simulating the thermodynamic performance of the packed bed which could result in significant over or under sizing of the PBR.

Experiments were conducted using a scaled-down PBR, using nitrogen as a working fluid passed through a gravel packed bed. The experimental temperature profile along the length of the packed bed was compared with the Schumann (Willmott, 2002) model and the White et al. (2014) model from the literature. The comparison was conducted at multiple stages during the charging of the PBR, using Matlab. Neither model was able to accurately predict the temperature profile through the packed bed, with a lower gas temperature predicted across the range of mass flow rates and charge times. We believe that this discrepancy in the agreement is largely due to the lack of accurate material properties at such low temperatures and assumptions made in the simulation. The particle size was assumed to be of uniform shape and diameter but the gravel varies in both size and shape, affecting the void fraction and conduction. The simulations do not include wall effects, which are higher in the lab-scale packed bed than those of a commercial packed bed. This is due to a higher particle to packed bed diameter ratio resulting in the path of least resistance for the flow being along the wall rather than through the bed.

INTRODUCTION

A packed bed regenerator (PBR) is used to store energy thermally in a solid medium. A gas, traditionally at high temperatures, is passed through the PBR and the heat is transferred into the solid medium. This study focuses on the use of cryogenic PBR's, where the gas passed through the system is at temperatures below 150 K. This process is referred to as charging the PBR. The cold can then be extracted from the solid medium, or discharged, to generate electricity on demand. Early models, including the Schumann model, were based on a single charge (Keil et al. (2012)). These models have been adapted through literature to consider the effects of a cyclic process. This has a consequence on the system losses, which vary between single and cyclic operation (White et al. 2014). The length of time that the heat can be stored is a function of the materials used and the geometry of the PBR. The material considerations can refer to both the gas and the solid medium. For example, cryogenic fluids can be stored in insulated vessels at low pressure (Morgan et al. 2015), which can reduce the required wall thickness and safety implications, but the material must be suitable for low temperature use. The geometry of the solid medium is a dominant factor to consider. Smaller material particles are preferred over larger particles due to the increased surface area which will aid in heat transfer. Ideally, the particles are uniform in size and shape. This allows for accurate calculation of the void fraction, pressure drop and the heat transfer between the particles. However, uniform particles are very expensive to manufacture in large quantities. Due to the low processing costs and availability of material, gravel is a suitable solid medium for packed beds. Although gravel is non-uniform, it can benefit from a larger surface area which can aid heat transfer between the particles. Geometric variations increase errors in simulating the flow between the particles due to an unknown void fraction and potentially higher pressure drops. The shape of the particles influences how tightly the bed can be packed and hence how much material is available for storage as well as the void fraction and consequently the pressure drop. Achenbach (1995) noted that the void fraction is higher near the PBR walls, due to the stacking of particles. This results in a non-uniform pressure drop across the bed and hence changes in the velocity profile and temperature front radially. This is especially true for non-uniform particles, such as gravel. Due to the large number of variables in question, modelling has been used to evaluate the required trade-offs. Modelling allows for the PBR geometry to be thoroughly investigated, for heat transfer and cost effectiveness. Simulation can be used to investigate the heat transfer mechanisms and interactions between: solid and fluid, fluid and PBR wall, and between particles. The validity of simulation is limited if the materials used for construction do not have well defined properties. In this case, these properties may need to be defined experimentally. This is particularly important when using novel materials or cryogenic temperatures, where limited material properties are available. Chai et al. (2014) investigated the effect of system pressure on the temperature profile through a PBR using 9 mm pebbles and liquid nitrogen. Pebbles were sifted using two meshes, to improve particle diameter consistency and allow for an estimation of the void fraction. The two pressures investigated were 0.1 MPa, representative of atmospheric pressure, and 6.5 MPa, representing supercritical conditions. The temperature profile, for both charging and discharging, were pressure dependent, with a thermocline evident. The system pressure also influenced the radial temperature profile, with a temperature difference between the centre of the PBR and the wall at a low pressure.

Many models in literature are adapted from the Schumann model, presented in Willmott (2002), which was produced to predict the temperature profile along a PBR using air. The Vortmeyer and Schaefer (1974) model, simplified the two phase Schumann model to a single phase model which included the axial thermal conductivity. The model was adapted for systems where the solid phase thermal conductivity is considerably larger than the gaseous phase. Mawire et al. (2009) adapted the Schumann model to investigate the three possible solid storage materials, fused silica, alumina and stainless steel. These materials were evaluated based on axial temperature distribution, total energy stored, total exergy stored and transient charging efficiency. The study concluded that an important parameter for the thermal performance of a PBR is the total energy stored, amount of exergy stored and degree of thermal stratification. A good measure of thermal performance was a high ratio of total exergy to total energy. The 1D model showed a greater accuracy in predicting the experimental temperature distribution compared with the Schumann model. The biggest variance between the simulated and experimental data was at the centre of the PBR. This difference could be a result of heat losses and uncertainties in the experimental system or the centre of the PBR being the greatest point of thermal mixing which is not represented in the models. These models predict a constant heat transfer coefficient across the length of the PBR, calculated from the material properties and inlet parameters, this limits their ability to predict the effect of mixing. Hänchen et al. (2011) conducted experiments in a PBR with four different materials. Similar temperature profiles were seen for both aluminium and rock, which have vastly different thermal conductivities, 204 and 0.48 $Wm^{-1}K^{-1}$, respectively. The controlling thermodynamic property was the volumetric heat capacity, which were similar for aluminium and rock at 2419 and 2458 $kJm^{-3}K^{-1}$, respectively. The aluminium and rock temperature profile advanced faster through the PBR than for steatite and steel, which had lower overall efficiencies. Steatite and steel had a shallow temperature profile through the packed bed, with thermal conductivities of 25 and 50 $Wm^{-1}K^{-1}$, and volumetric heat capacities of 2862 and 4454 $kJm^{-3}K^{-1}$, respectively. It is noted that thermal expansion is not considered which will be greater for metals than rocks. The particle to fluid convective heat transfer was shown to have a strong influence on the shape of the temperature profile, with the smallest particle size having the highest efficiency. The largest capacity factor was achieved with a high mass flow rate, low PBR height and volumetric heat capacities, but at the expense of a lower overall efficiency. The experimental results were compared with three models from literature. The particle to fluid convective heat transfer had a strong influence on the shape of the temperature profile, which differed between the three models. The model which showed the best agreement with experimental data, and had the intermediate convective heat transfer as a function of mass flux, uses the same correlation as the Schumann model, see Equation 1. The convective heat transfer (α_p) is a function of the particle diameter (d), mass flux (G) and void fraction (ε). The utilisation of gravel or non-uniform particles will require assumptions on the particle diameter and void fraction, which will consequently limit the accuracy of the temperature profile prediction.

$$\alpha_p = \frac{700}{6(1-\varepsilon)} G^{0.76} d^{0.24} \qquad (1)$$

Models in literature are contradictory on which parameters are important to accurately predict the temperature profile through a PBR. The models are adapted to suit specific experimental conditions, commonly from the Schumann model (Willmott, 2002) for high temperature PBR's, where material properties are available in literature. White et al. (2014) conducted simulations for the temperature profile through both hot and cold PBR's. For the current study, two models were used for comparison with experimental data. The Schumann model (Willmott, 2002) and the White model (White et al. 2014). Assumptions over the thermodynamic processes are required for simulation. The original Schumann model assumed the following;

- Fluid flow through the packed bed is laminar and incompressible
- The fluid and packed bed particle temperatures are functions of the co-ordinates in the flow direction only.
- Biot number is sufficiently small so the temperature distribution can be considered uniform in the packed bed particles.
- Conduction in both the fluid and the packed bed particles is negligible.
- Properties of the packed bed particles and fluid are constant.
- Radial variation of the fluid properties is neglected.

White et al. (2014) concluded that further parameters were required to accurately evaluate the temperature profile and adapted the Schumann model to include the pressure gradient and the influence of the solid phase particle size. The method used for evaluating the heat transfer coefficient was adapted to include the void fraction, which is an important parameter in the pressure drop.

METHODOLOGY

A scaled down PBR was constructed in the laboratory, with an adiabatic tank 1840 mm high and 303 mm in diameter, see Figure 1. The tank perimeter walls are 34 mm thick PTFE. Inlet and outlet chambers act as manifolds, distributing the gas evenly. The gravel, or solid medium, has a height of 1444 mm. The gravel, which was commercially sourced, is tightly packed within the bed. Thermocouples measure the temperature of the gas at the inlet and outlet, in the inlet and outlet chambers and throughout the gravel at equally spaced distances of 150 mm. Liquid nitrogen (LN_2) is passed through an evaporator to ensure that only nitrogen gas enters the PBR. As the nitrogen gas passes through the PBR, the temperature will increase. This warmed gas is used in the evaporator which, with the use of a bypass, can be used to control the inlet temperature of the PBR. The flow rate of the gas is measured at the outlet of the PBR.

The position of the thermocouples can result in experimental uncertainties. The thermocouples were positioned so that the tip is at the centre of the packed bed. The temperature reading could be that of the gravel surface or the gas flow, although the difference between the two would be small - less than 8 K. If the thermocouple is recording the temperature of the gas only, the temperature may fluctuate as a result of thermodynamic structures in the flow, such as mixing.

The thermocouples, pressure sensors and flow meter measurements were recorded using an instruNET datalogger at a rate of 1 Hz. The raw data was processed in Matlab, plotting the individual thermocouple data, temperature profile along the length of the tank and mass flow rate as a function of time.

Experiments were conducted at four mass flow rates, low flow (0.00312 kg/s), medium flow (0.00562 and 0.00716 kg/s) and high flow (0.01235 kg/s). This allowed for the effect of the flow rate on the temperature profile through the packed bed to be investigated.

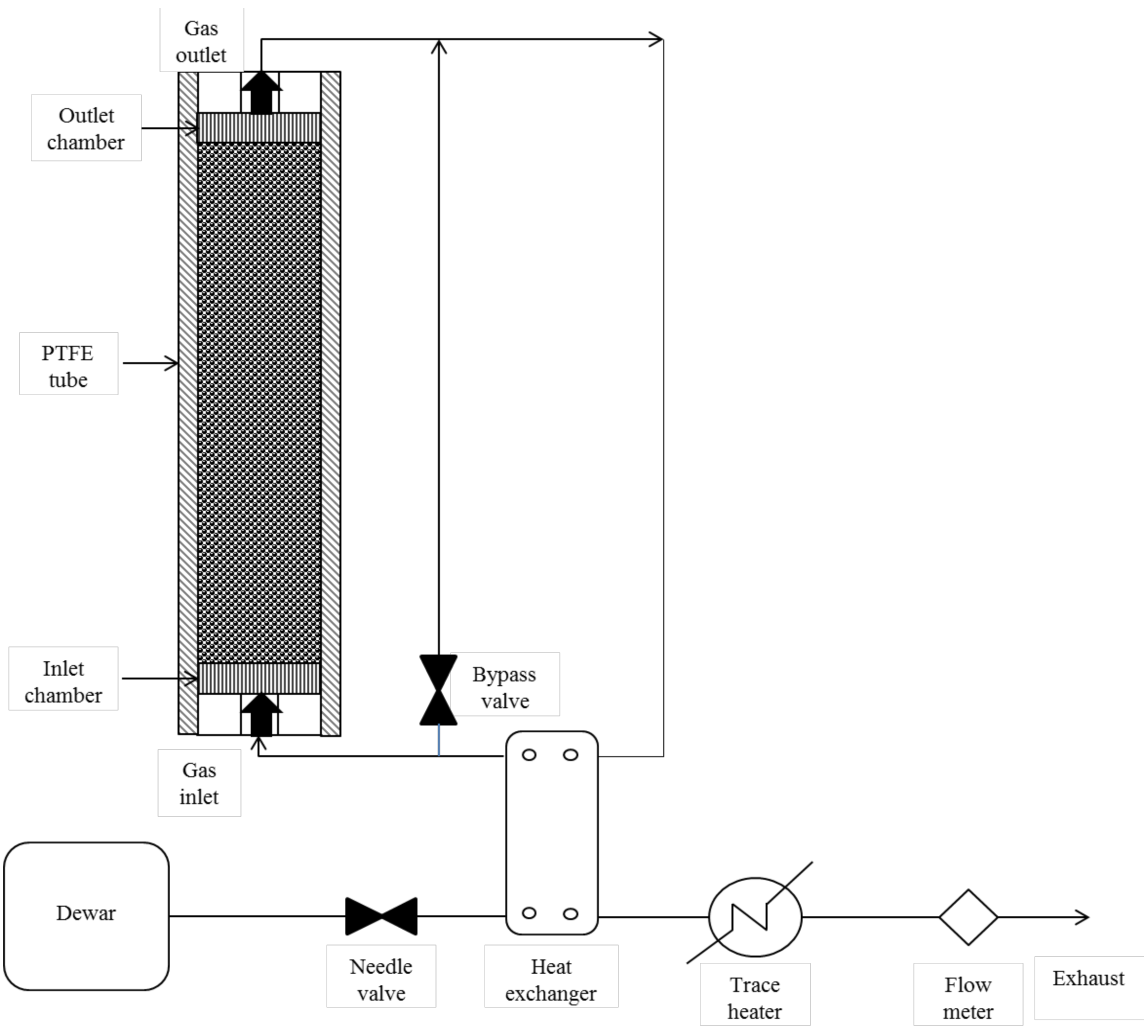

Figure 1. Schematic of the lab scale PBR.

The experimental data was compared with the Schumann model and the White model using Matlab. These models require material properties for both the solid phase (gravel) and the liquid Nitrogen. The properties of liquid Nitrogen (density, specific heat capacity, conductivity, and viscosity) were taken from Engineering Equation Solver (EES). The thermophyscical properites of the gravel (density, specific heat capacity and thermal conductivity) were evaluated from experiments on four gravel samples. Each sample consisted of a range of gravel compositions and sizes to give an accurate representation of inside the PBR. The density was calculated from the water displacement technique, with the gravel samples measured both dry and wet to account for porosity. The specific heat capacity was evaluated from an energy balance of the mass of evaporated liquid nitrogen when the gravel samples are submerged with the known enthalpy of the liquid nitrogen to the mass and temperature change of the sample (Pike-Wilson et al. 2015), see equation 2.

$$Q = \left(m\, c_p\, \Delta T\right)_{sample} = \left(m_{evap}\, h\right)_{fluid} \tag{2}$$

The thermal conductivity of the gravel was calculated based on the comparative conductivity method (Czichos et al. (2006)). The comparative method comprises of measuring the temperature profile across a known material, stainless steel in this instance, which encloses the sample. The thermal conductivity is evaluated from the temperature resistance across the stainless steel and gravel sample. One end of the stainless steel was placed in to liquid nitrogen and the other was at ambient temperature with thermocouples positioned along both stainless steel blocks and the gravel bed. A PTFE sleeve was used to insulate the gravel and reduce radial effects.

The void fraction was estimated from measuring the volume of gravel which could be packined into a cylinderical container, giving a void fraction of 0.47. Chai et al. (2014) calculated the void fraction to be 0.4, with an average particle diameter of 9 mm, based on the definition of Achenbach (1995). Assuming a perfect spherical particle, the minimum void fraction possible is 0.26. A higher void fraction would be expected due to the irregular particle sizes and packing. In the lab scale PBR, the void fraction should be a value between the minimum and that of the thermal conductivity rig. Due to the smaller particle size to tank diameter ratio, the packing density would be lower. The particle size was taken to be 0.02 m, based on the average diameter of the gravel samples.

RESULTS

The temperature profile along the length of the PBR was evaluated at three mass flow rates. The mass flow rate of gas is an important parameter for the efficiency of a PBR. A slow charge time can be desirable for commercial use but a very short charge time could result in the gravel not reaching the desired temperature. The required charge time is a function of the solid medium properties, namely the specific heat capacity. There is little data available in literature on the thermodynamic properties of rock at low temperatures so these properties need to be evaluated experimentally for simulation purposes. The specific heat capacity was taken to be 504 $Jkg^{-1}K^{-1}$, the average of two tests for four samples, with a standard deviation of 14 $Jkg^{-1}K^{-1}$. This is within the same range in literature for pebbles at low temperatures, (Chai et al., 2014). The thermal conductivity was measured as 4.11 $Wm^{-1}K^{-1}$ and the density as 2489 kgm^{-3}.

Figure 2 presents the temperature profile in the lab scale PBR as a function of mass flow rate and charge time. As expected, the temperature profile at a given time varies with the mass flow rate. As the flow rate is increased, the amount of nitrogen entering the PBR is higher and as a result, more cold is stored as a function of time. As seen in Figure 3, the storage capacity is the same for all mass flow rates but the length of charge required to reach this point will vary with mass flow rate.

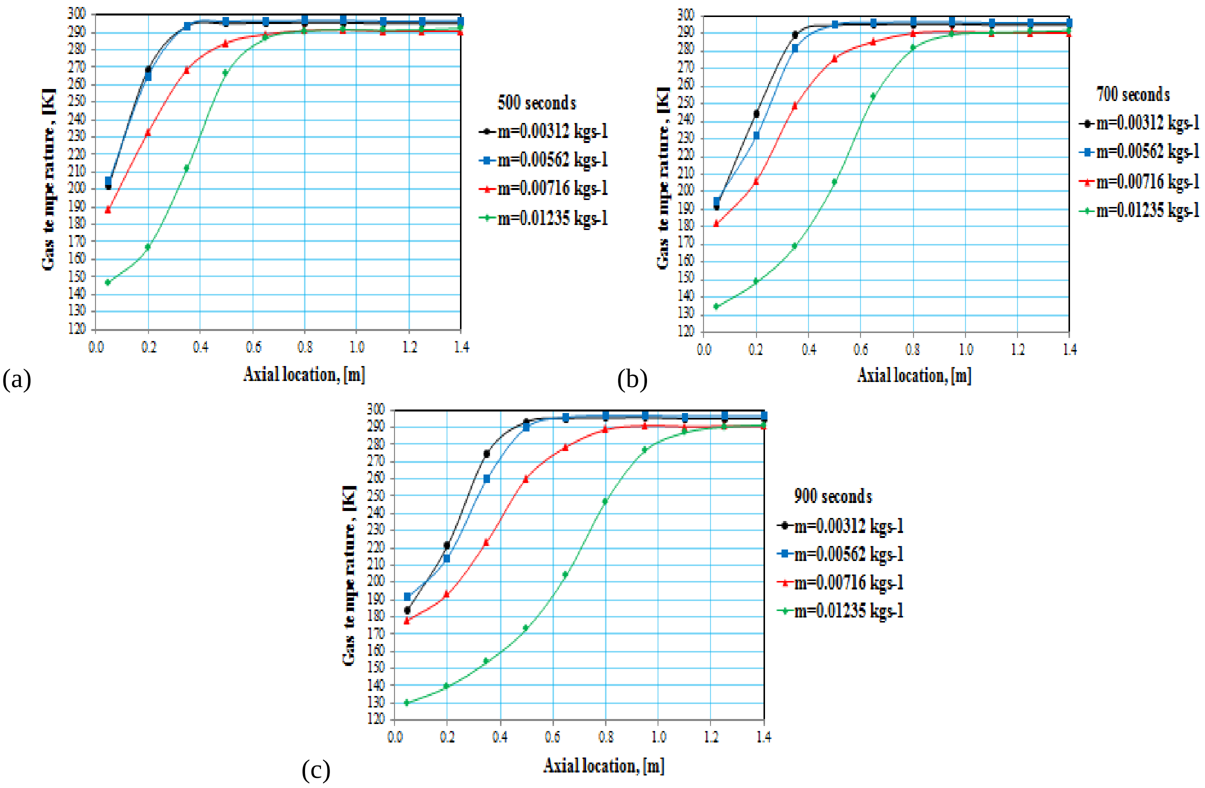

Figure 2. Experimental temperature profiles at (a) 500 seconds, (b) 700 seconds and (c) 900 seconds.

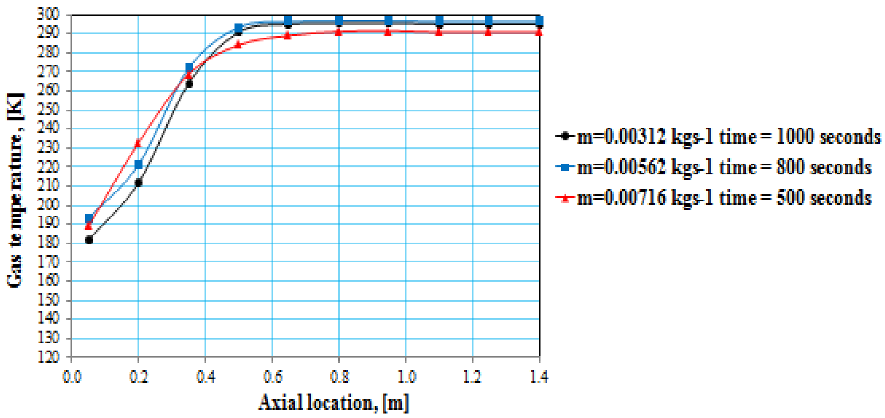

Figure 3. Experimental temperature profiles for three mass flow rates at varying charge times.

The temperature profile along the length of the PBR was compared as a function of time with the Schumann (Willmott, 2002) and White (2011) models for evaluation. Figure 4 shows the comparison of the two models with the experimental data for all three mass flow rates at a time of 1100 seconds. The differences seen between the experimental data and the two models could partly be due to mass flow rate fluctuations, due to the evaporation of the nitrogen and temperature changes, with the experimental mass flow rate based on the averaged values. The mass flow rate was controlled using a needle valve from the liquid nitrogen Dewar and monitored using the data logger. The mass flow rate was recorded at the exit and may be affected by the pressure drop and thermodynamic processes within the PBR. At the lowest mass flow rate, 0.00312 kgs^{-1}, the measured gas temperature is lower than predicted by both models. As the flow rate increases, the measured temperature profile falls between the two models.

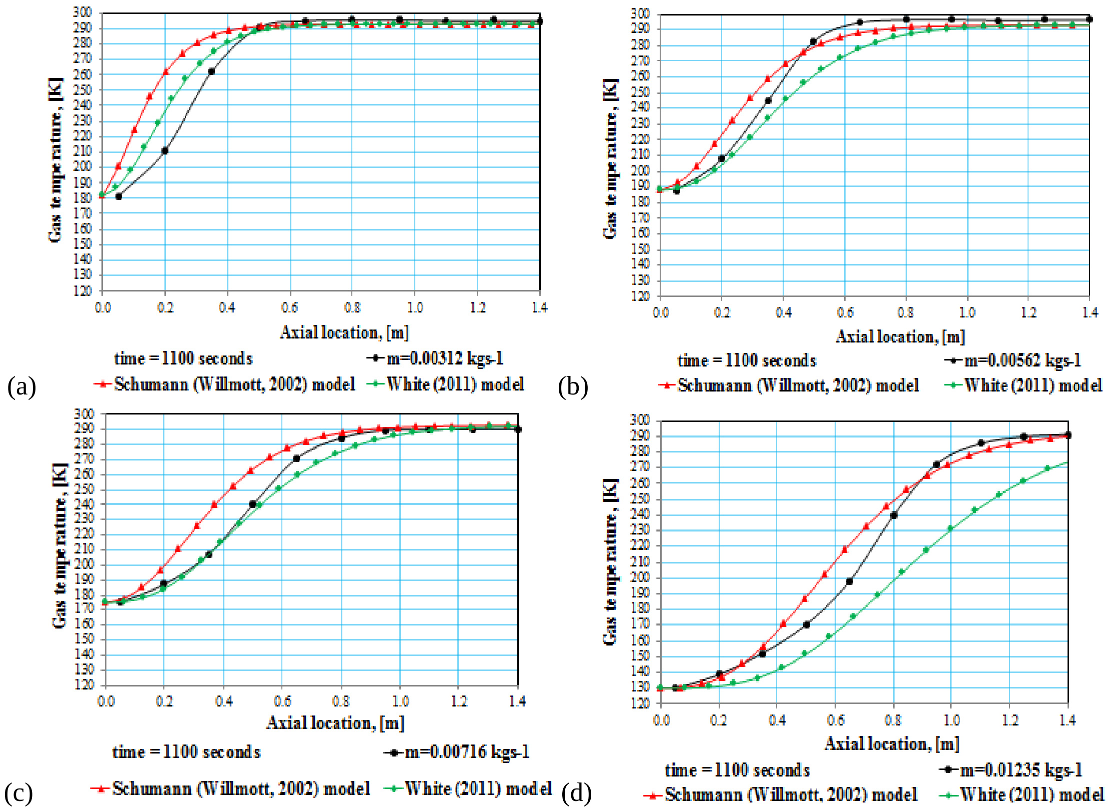

Figure 4. White (2014) and Schumann (Willmott, 2002) model compared with experimental data for mass flow rates of (a) 0.00312 kgs^{-1}, (b) 0.00562 kgs^{-1}, (c) 0.00716 kgs^{-1} and (d) 0.01235 kgs^{-1}.

Figure 5 compares both models at the lowest and highest flow rates at a charging time of 500 seconds. Contrary to the results at 1100 seconds, both models predict a lower temperature and, for the highest mass flow rate, a difference in the temperature profile trend. These results show that the heat transfer coefficient was lower in the lab scale PBR than predicted by either model. At the lowest flow rate, the heat transfer coefficient was predicted by the White (2011) model and the Schumann (Willmott, 2002) model to be 236 and 233 W/m^2K, respectively. This equates to Biot numbers in the region of 30. The experimental results showed a heat transfer coefficient of 190W and a Biot number of 18. The experimental Biot numbers were calculated to be between 18 and 20, lower than those of both the White and the Schumann models.

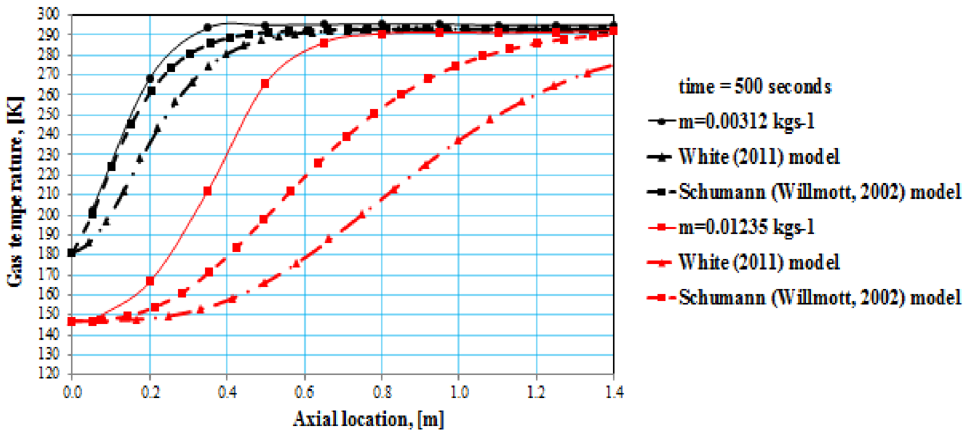

Figure 5. Comparison of the simulated and expeirmental data at a charging time of 500 seconds

The simulated temperature profiles, for both models, show a lower predicted gas temperature with the thermal front propagating through the packed bed faster than seen experimentally. This equates to an over-prediction of the amount of cold being stored experimentally for a given charge time, which will affect the design and implementation of cryogenic packed beds. There could be many variables which will affect the accuracy of the models, including the scale of the lab packed bed. The models do not include any functions of radial heat transfer or wall effects, which will be more prevalent with a small scale rig. Hänchen et al. (2011) noted that agreement between models and experimental data from a pilot plant was achieved by reducing the simulated mass flow rate by 15%. This is based on a lab scale PBR, 1.2 m high and 0.148 m diameter, giving a cross sectional area of 0.0172 m. This is less than a quarter of the cross sectional area of the lab scale PBR used for the current experiments. Figure 6 shows that changing the mass flow rate does improve the accuracy of the results, with an increase of 69 % in the mass flow rate. The lab scale rig was insulated with Armaflex cryogenic insulation, 25 mm thick with a thermal conductivity of ≤ 0.04 $Wm^{-1}K^{-1}$. There is an approximate heat loss of 257 W through the insulation and PTFE tube, which would equate to 33 % of the energy lost for a mass flow rate of 0.00562 kgs^{-1}. The remaining 36 % of energy loss is likely a due to the result of scaling which will increase the wall effects. This suggests that for small scale rigs, a mass flow rate coefficient could be used to compensate for the change in scale.

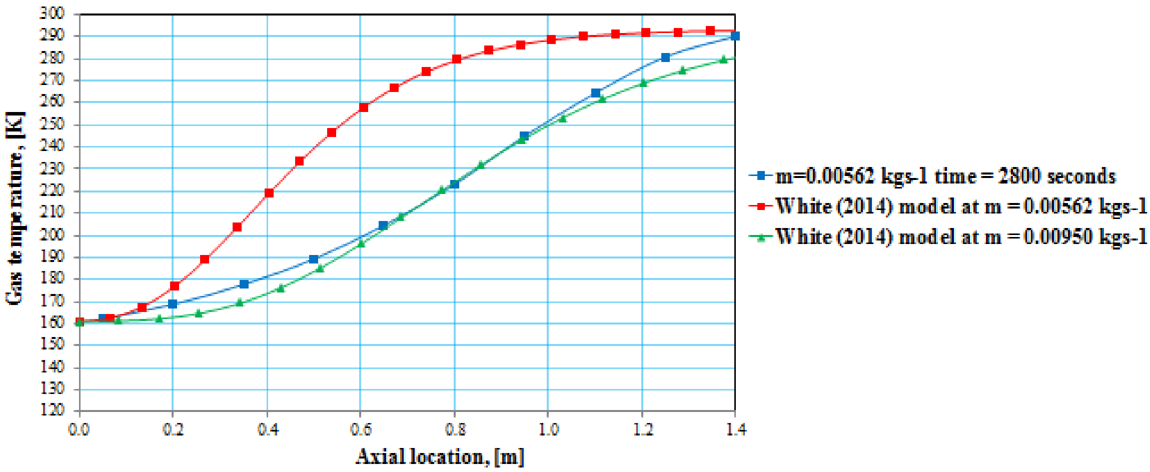

Figure 6. Experimental and simulated temperature profile which adjusted mass flow rate value.

Although the governing equations are based on the conservation of mass, the use of a mass flow rate coefficient will not affect the simulation. The White (2011) model discounts mass continuity and thermodynamic property variations to simplify the model. White (2011) assumes constant thermodynamic properties and a constant mass flow rate. The White (2011) model predicts an increase in the temperature profile gradient across the length of the PBR, contrary to the experimental results. As a result, the steady state equations are solved independently from the momentum equation, assuming the working fluid to be a perfect gas. The mass flow rate is a function of the length and time scales, used to normalise the results. However, changing the thermodynamic properties as a function of the temperature improved the comparison between the simulated and experimental data. The mass flow rate coefficient remained constant over time for each test condition when material properties were updated, but was seen to vary when the properties were kept constant. This implies that these changes in properties should be considered when simulating flow through a PBR.

DISCUSSION

Discrepancies between the models and experimental data could be a result of the changes in the thermophysical properties, assumed constant in the models, which will change with temperature, and assumptions of void fraction and particle size. The models were run with variations in the material and fluid properties, across a range that would be expected for the experimental temperatures.

The assumed values for the properties of the nitrogen (density, thermal conductivity, specific heat capacity and viscosity) were varied between 161 and 300 K for each model. There was minimal effect on the Schumann (Willmott, 2002) model, due to the heat transfer being a function of the experimental conditions. The specific heat capacity is used as part of the length scale, defining the corresponding axial location of the predicted gas temperature, but this showed a minimal effect. This was also true for the White (2011) model, with the specific heat capacity being to the power of -0.3, and therefore having negligible effect on the gas temperature. The fluid density, although included in the equations, has no effect on the calculation of the heat transfer coefficient. However the thermal conductivity was shown to affect the predicted gas temperature for the White (2011) model. Increasing the thermal conductivity values across the temperature range showed up to a 10 K higher gas temperature at the same axial location. The effect of thermophysical properties were evident when a mass flow rate coefficient was also used. Figure 7 compares the experimental data with the Schumann model, with varying thermodynamic properties. This model varied both the air properties (viscosity, heat capacity, thermal conductivity, density) and the heat capacity of the gravel. The property values were evaluated based on the measured temperature. Across the three mass flow rates tested, the predicted temperature profile shows a good agreement with the experimental data. When the thermodynamic properties are varied, the mass flow rate coefficient remains constant for a given experimental configuration.

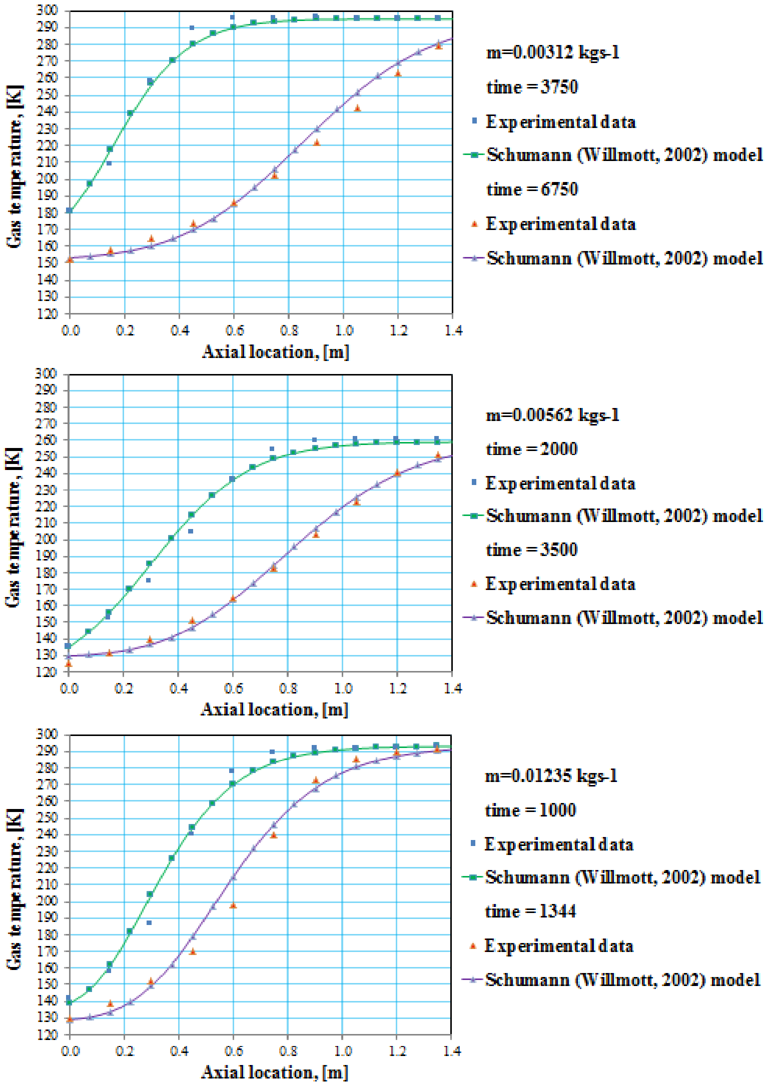

Figure 7. Comparison on the Schumann (Willmott, 2002) model with varying properties across three mass flow rates.

The properties of the gravel, namely conductivity and density, showed very little variation in value and had no effect of the predicted temperature. This was expected as for both models, the heat transfer coefficient is only a function of the experimental conditions, void fraction and particle size. The particle size used in the models is 0.02 m, which is based on the average dimensions of the gravel and that stated from the supplier. However, the gravel varies in size from 0.005 to 0.03 m and is not spherical. This will have an effect on the packing density and void fraction of the PBR. The particle size is used to calculate the heat transfer coefficient for both models, to a negative index meaning that an increase in the particle size will reduce the heat transfer coefficient and decrease the predicted gas temperature. Figure 8 presents the temperature profiles for the Schumann (Willmott, 2002) model and the White (2011) model at 1200 seconds for a mass flow rate of 0.0051 kgs^{-1}, with particle diameters of 0.005 and 0.03 m. The temperature profile changes in shape with the particle diameter for both models, with a steeper thermal front with a larger diameter particle. White et al. (2014) stated that the length scale should be as small as possible, in addition to a smaller particle diameter, to reduce the irreversible heat transfer. However, reducing the particle diameter will increase the pressure losses in the vessel. A smaller particle diameter reduces the temperature difference between the gas and the gravel. Therefore there is a tradeoff between having a more favourable temperature profile but higher pressure losses.

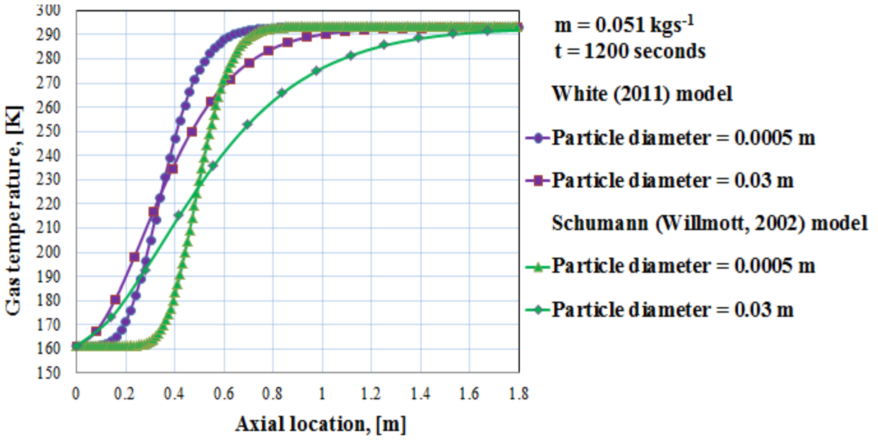

Figure 8. Simulated temperature profiles with different particle diameters.

This is based on particles of uniform diameter which is not applicable with gravel. The irregular shapes will also have an effect on the conduction through the packed bed, with the surface area in contact between the particles differing from that of uniform shapes. The contact surface area between the particles could be higher or lower than expected, depending on the packing, and could also change due to thermal expansion of the PBR tank during use. Possible conduction in both the gravel and the air is ignored in the models, which could affect the temperature propagation. This will depend largely on the material used in the PBR, with minimal conduction expected for gravel. Simulations were run which varied the void fraction from 0.27 to 0.47, see Figure 9. For both models, the predicted gas temperature is lower with a higher void fraction, with a higher quantity of cold stored at a given time. The White (2014) model incorporates the void fraction as a function of the length scale, which defines the shape of the predicted thermal front and the corresponding axial location for a given gas temperature.

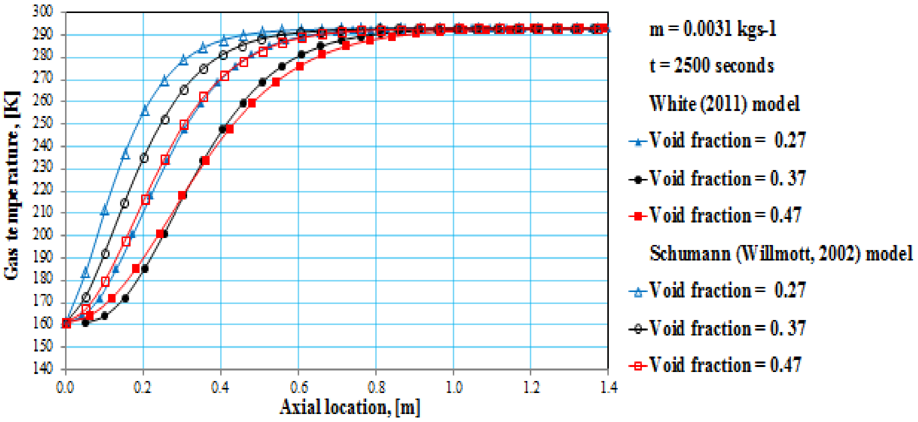

Figure 9. Simulated temperature profiles with a change in the void fraction.

A larger void fraction could reduce wall effects, which are neglected in both models, as there would be less resistance to flow through the bed, but increases the size of the packed bed for a set storage capacity. Wall effects will be greater for the lab scale rig due to the smaller ratio between the particle and tank diameters. The pressure drop will increase with decreasing void fraction which is a greater concern for cold reservoirs, which already have a higher pressure drop than hot reservoirs due to the lower operating pressure.

CONCLUSIONS

Experiments were conducted on a lab scale packed bed regenerator, using commercial grade gravel and liquid nitrogen. Equidistant thermocouples along the length of the packed bed allow for the thermal front to be plotted as a function of the axial location, as well as the charge time and mass flow rate. The experimental results were compared with those of two models from literature, the Schumann (Willmott, 2002) model and the White et al. (2014) model. The predicted temperature profiles were lower than that seen experimentally, across all mass flow rates and charge times. Therefore, the volume of cold which could be stored was less than predicted, with many possible reasons for these discrepancies. The three main areas of error are the effect of the PBR scale, greater losses due in cold reservoirs and the assumptions made for the models. The lab scale rig has a smaller particle to bed diameter ratio and therefore the path of less resistance for the flow will be along the wall. Wall effects are ignored in both models, as is a radial temperature profile which will be likely be evident in the small scale rig due to the larger wall effects and non-uniform particle sizes. The ratio of particle to bed size will also impact the void fraction, which due to the irregular sized particles, is likely to be larger in the lab scale rig. The models are based on hot reservoirs, with cold reservoirs having higher pressure losses due to the lower operating pressure. The models assume that there is no radiation or conduction in either the fluid or gravel and that the thermophysical properties remain constant. The fluid properties will vary over the operating range, 161 – 300 K, which will affect the heat transfer coefficient. The particles are assumed to be spherical and of consistent diameter. The irregular particles vary in size and, due to the packing structure, will have a higher contact area between the particles which could increase the heat transfer through conduction. The simulations over-predict the available cold storage in a given time period, which would affect the sizing of the design. Hänchen et al. (2011) concluded that the particle to fluid convective heat transfer has a strong influence on the shape of the predicted temperature profile. Assumptions of the particle diameter and void fraction will reduce the accuracy of the predicted convective heat transfer and the temperature profile.

One possible solution is to include a mass flow rate coefficient which would compensate for the scale affects. Further modifications are required to future models which account for both the effect of particle size and thermodynamic interaction between particles.

NOMENCLATURE

Notation		Units
d	particle diameter	M
C_p	Specific heat capacity	$Jkg^{-1}K^{-1}$
G	Mass flux	$Kgm^{-2}s^{-1}$
h	Enthalpy	Jkg^{-1}
m	Mass	Kg
Q	Heat transfer	W
T	Temperature	K
Greek letters		
α_p	Particle to fluid convective heat transfer	$Wm^{-2}K$
ε	Void fraction	-
Subscripts		
fluid	Liquid Nitrogen	
evap	Evaporated	

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