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THEORETICAL AND EXPERIMENTAL STUDIES OF A THERMAL REGENERATOR FOR HEAT RECOVERY IN ALUMINUM MELTING FURNACES

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Abstract

Nowadays, energy consumption has been proposed as one of the major indexes in evaluation of community development. For this purpose, different types of heat recovery systems have been designed and built. One of these systems is a fixed-bed regenerator (FBR) that has widespread applications in energy industries such as glass and aluminum. In aluminum melting furnaces such systems can be utilized to preheat air by absorbing heat from flue gases from the combustion chamber which results considerable fuel consumption in the furnace. Due to the high temperature application of such systems in aluminum furnaces, the packing must be constructed from ceramic with very low thermal conductivity and the mechanism of heat transfer will be convection and radial conduction inside the spherical packing. This paper presents the results of the mathematical modeling and simulation studies of a fixed bed regenerator filled with spherical shape packing made from alumina with different diameters. For the modeling purposes two mathematical models have been considered; simplest convection model and more complex radial conduction model inside the packing particles. For evaluation of the model and to study the effect of different parameters such as gas mass flow rate, period time and ball diameter on the performance of the system, an experimental setup has been designed and built. The results clearly show that decreasing of gas mass flow rate, period time and packing diameter increase the system efficiency.

Introduction

Increasing cost of fuels, decreasing of fossil fuel resources and necessity to control environmental pollutions, Show the importance of recovering of thermal energy and preventing of its destruction in different industries. Sharp increase of energy consumption in manufacturing processes causes an increase in the production and application costs and also a decrease in efficiency of materials recovery in industrial products. Increasing the efficiency of energy consumption and decreasing of the wastes are available with design of systems of optimized thermal recovery. One of important and energy intensive industries is aluminum melting industry which has a high density of energy consumption in part of the melting furnaces. Therefore, this part of the process has to be taken into consideration for increasing of efficiency and decreasing of energy consumption. Aluminum melting furnaces often have wasted gases with temperatures between 700 -1000°C which are suitable resources for heat recovery and increasing of production efficiency [1,2]. Among the most important efficient methods in this context is utilization of fixed bed regenerator for recovery of wasted heat from aluminum melting furnaces.

Regenerators are compact heat exchangers, filled with high heat capacity solids, which absorbs the heat from the flue gases in one period called hot period, and releases to the air used for the combustion in the burners in the cold period. One of most important design parameters in regenerators is a high surface area per unit volume [3]. Regenerators can transfer both sensible and latent heat. They are mainly used in two types: fixed- bed (FBR) and rotary.

The operation of regenerators is periodic. In the first period, called hot period, hot flue gases flows through the bed and transfers the heat to the packing. After a certain period time the hot gas flow is stopped. The cold air flow is then passed through the bed counter currently, absorbs the heat from the packing and is preheated.

Summation of these two periods counts as a cycle in the regenerator operation. Due to the periodic operation of the FBRs, at least two beds are required for a continuous operation. The advantages of using a FBR can be listed as following [4]:

1-Only one channel is needed for entry of hot and cold gases inside this system.
2- High heat transfer area exists per unit volume.
3- Uniformly pressure distribution in regenerator system.
4- Opposite direction of two internal streams leading to a clean heat transfer operation, so no sediment is remained in the device.
5- During the process of heat transfer in FBRs, any impurity droplets on the solid surface will be removed by the hot gas flow in the next period.

Modeling

Figure 1 represents the regenerator domain for the mathematical modeling. The following simplifying assumptions are made for the system modeling [5,6]:

1-Thermophysical properties of the gas and solid are constant.
2- The temperature and the flow rate of the gas to the bed do not change with time.
3-Transverse area of bed is constant along the bed.
4- Longitudinal thermal conductivity in the gas is neglected.
5-Direction of gas streams in the hot and cold periods are opposite to each other and this event prevents from sedimentation in bed.
6- All balls in the bed are identical and have similar size.
7-Regenarator is considered as a thermal insulator and there is no heat loss from the regenerator's wall.
8-There is no energy source in the regenerator.
9- No chemical reaction occurs in the bed.
10-Balls are in spherical shape and have a single contact point which results negligible axial conduction in the balls.

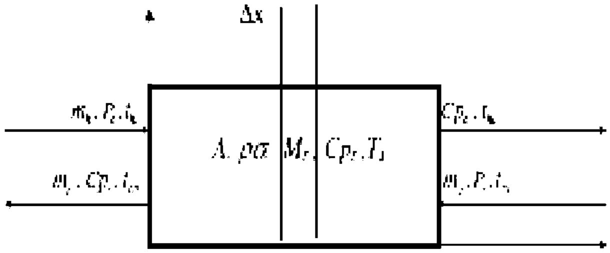

Figure 1. Representative computational domain [1]

With segmentation of system to two gas and solid phases, we have for the hot period:
- Gas phase

$$\dot{m}_f C_p L \frac{\partial t_f}{\partial y} = hA\left(t_s - t_f\right) - m_f C_p \frac{\partial t_f}{\partial z} \quad (1)$$

-Solid phase

$$\frac{\partial^2 t_s}{\partial r^2} + \frac{2}{r}\frac{\partial t_s}{\partial r} = \frac{1}{\propto}\frac{\partial t_s}{\partial z} \quad (2)$$

Boundary conditions of the system are defined as:

$$\frac{\partial t_s}{\partial \mathrm{r}} = 0 \qquad @r = 0 \quad (3)$$

$$-K_S \frac{\partial t_s}{\partial r} = h\left(t_{ss} - t_f\right) \qquad @ \quad r = R \quad (4)$$

The initial conditions of the process are defined as:

$$\boldsymbol{t_f(y, 0) = \text{apparent}}$$
$$t_f(y, 0) = \text{apparent} \quad (5)$$

In order to solve the model, all equations can be redefined using the following dimensionless parameters.
Dimensioneless temperature:

$$T = \frac{t - t_{s,0}}{t_{f,in} - t_{s,0}} \quad (6)$$

Dimensionless coordinate location and radius:

$$\xi = \frac{hA}{\dot{m}_f C_p L}\, y \qquad , \quad Z = \frac{r}{R} \quad (7)$$

Dimensionless residence time:

$$\eta = \left(\frac{hA}{MC_s}\right)\left(\tau - \frac{m_f}{\dot{m}_f L}\, y\right) \quad (8)$$

For equation (1) which is relevant to y and Z variables, in addition to the previous relationships, derived change techniques has been applied to change the equation to dimensionless coordinate form. Using the chain rule the dimensionless form of equation (1) will be as follows:

$$\frac{\partial T_f}{\partial \xi} = T_s - T_f \quad (9)$$

And for the solid phase assuming the Biot number definition for the spherical packing and thermal diffusion inside the spheres we have:

$$\frac{\partial T_s}{\partial \eta} = \frac{1}{9B_i}\left[\frac{\partial^2 T_s}{\partial Z^2} + \frac{2}{Z}\frac{\partial T_s}{\partial Z}\right] \quad (10)$$

Initial and boundary conditions in the form of dimensionless are:

$$\frac{\partial \boldsymbol{T_S}}{\partial \boldsymbol{Z}} = 0 \qquad @ \quad Z = 0 \quad (11)$$

$$\frac{\partial \boldsymbol{T_S}}{\partial \mathbf{Z}} = -3\mathrm{Bi}(\mathrm{T_{ss}} - \mathrm{T_f}) \;\; @ \;\; \mathrm{Z} = 1 \quad (12)$$

$$T_{f,in} = 1 \;\; , \;\; T_{s,o} = 0 \quad (13)$$

Two important variables of dimensionless numbers for description of behavior of FBR are reduced length (14) and reduced period (15) which is defined as follows [7]:

$$\Lambda = \left(\frac{hA}{\dot{m} Cp}\right) \quad (14)$$

$$\Pi = \frac{\mathrm{hA}}{\mathrm{MC_s}}\left(P - \frac{m_f}{\dot{m}_f}\right) \quad (15)$$

It is necessary to mentioned that all of these equations are exactly written for the cold period with prime mark on the variables. The ratio of reduced period to the reduced length is defined as utilization factor.

$$\mathrm{U} = \Pi / \Lambda \quad (16)$$

The ratios of utilization factors and reduced lengths for the hot and cold periods are defined as unbalance and asymmetry factors. The operation of regenerator is dependent of these two parameters. When both of these two parameters are unity the regenerator operates at symmetric-balances mode of operation. In the case of different utilization factors and reduced lengths the regenerator operates at asymmetric and unbalance mode. The latter case is more efficient than the former due to the variable flow rate and period times for each period. The efficiencies of the regenerator for the cold and hot periods are defined as:

$$\eta_h = \frac{(\dot{m}_f C_p P)_h\,(t_{f,in} - t_{f,x})}{(\dot{m}_f C_p P)_{min}\,(t_{f,in} - \acute{t}_{f,in})} \quad (17)$$

$$\eta_c = \frac{\acute{\dot{m}}_f \acute{C}_p \acute{P}(\acute{t}_{f.x} - \acute{t}_{f.in})}{(\dot{m}_f C_p P)_{min}\,(t_{f,in} - \acute{t}_{f,in})} \quad (18)$$

The average efficiency then can be calculated at equilibrium condition as:

$$\eta = \frac{\eta_h + \eta_c}{2} \quad (19)$$

Finite difference technique has been applied for the solution of differential equations. The equations have been rearranged in the algebraic form using advanced Euler method. For solid phase we have:

$$T_{s,i}^{n+1} = \left[1 - \frac{2\Delta\eta}{9\mathrm{Bi}\Delta Z^2}\right] T_i^n + \left[\frac{\Delta\eta}{9\mathrm{Bi}\Delta Z^2} + \frac{\Delta\eta}{9\mathrm{iBi}\Delta Z^2}\right] T_{i+1}^n + \left[\frac{\Delta\eta}{9\mathrm{Bi}\Delta z^2} - \frac{\Delta\eta}{9\mathrm{iBi}\Delta Z^2}\right] T_{i-1}^n \quad (20)$$

Explicit method of finite difference technique has been used with the required stability condition as:

$$\Delta\eta < \frac{9Bi\Delta Z^2}{2} \quad (21)$$

For the fluid phase using the advanced Euler method:

$$T_{f,j+1}^{n+1} = T_{f,j}^{n+1} + \frac{\Delta\xi}{2}\left[\frac{\partial T_f^{n+1}}{\partial\xi}\Big|_{j+1} + \frac{\partial T_f^{n+1}}{\partial\xi}\Big|_j^{n+1}\right] \quad (22)$$

To solve of differential equations of fluid phase from Euler method, a primary guess is needed which is estimated from simple Euler method. Finally for this phase:

$$T_{f,j+1}^c = T_{f,j} + \frac{\Delta\xi}{2}\left[(2 - \Delta\xi)\left(T_{s,j} - T_{f,j}\right)\right] \quad (23)$$

The heat transfer coefficient has been calculated using the correlation reported in the literature for the packed bed heat exchanger [4] based on the Reynolds and Prandtl numbers as [8-10]:

$$NU = 2 + 1.1Pr^{1/3}.Re^n\left(\frac{dp}{dh}\ \varepsilon\right)^n \quad (24)$$

Experiments

For the evaluation of accuracy of the model and study of the effects of different parameters such as mass flow, period time and diameter size of spherical balls on the operation of this system, one experimental setup from this system with alumina spherical balls have been designed and built as shown in Figure 2.

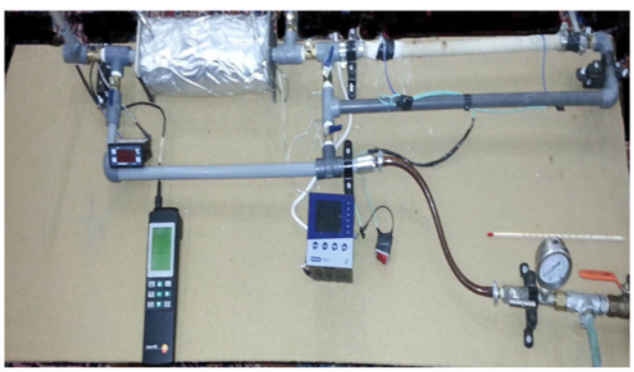

Figure 2. Regenerator experimental setup

The air has been used a gas phase in each hot and cold periods. For producing of the hot gas for the hot period, one electric heater has been used and installed at the entrance before entering of the air into the bed. The bed has been insulated with a layer of glass wool insulation for minimizing the heat loss to the surrounding. The air temperature of the cold and hot periods was considered at 25°C and 35°C respectively and initial temperature of the surface was considered 25°C to maintain the air constant properties. For measurement of the exiting flow from both periods, a platinum resistive thermometer was used. Specifications and properties of the ceramic balls and bed are listed in Table 1.

16 experiments have been performed using four flow rates for the entering gas i.e. 1, 2, 3, and 4 (m/s) and at four different period times i.e. 60, 80, 120, and 180 seconds for two different alumina packing sizes i.e. 0.8 and 1.5 Cm.

Results

Figures (3) and (4) show the comparison of the outlet temperature profiles for the first hot and cold periods with the model respectively. As shown in the figures for the hot cycle the model predicts higher out let temperature which is due to the heat loss of the system to the environment during the hot period. The inverse effect exists at the cold period when the heat loss is from the environment to the system which results lower outlet temperature prediction by the model.

Effect of entering Mass flow of gas and time period

In order to investigate the effect of all parameters, definition of efficiency from equation (16), (17) and (18) was used and the results are shown in Figures 5 to 7.

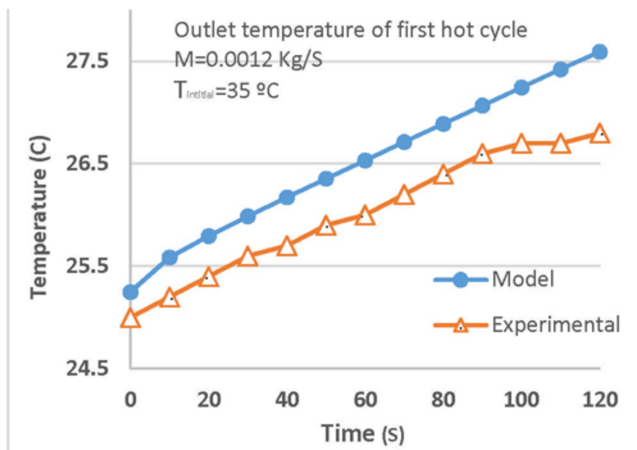

Figure 3. Outlet temperature of first hot period for 15 mm ball

Table 1. Specification of alumina balls

Spherical ball			
Thermal conductivity (W/m K)	2.1	Diameter (mm)	8 , 15
Specific heat (J/Kg K)	700	Mass (kg)	1.344
Density (Kg/m³)	3630		
Bed specification			
Length (mm)	300	Voidage	0.41
Diameter (mm)	85		

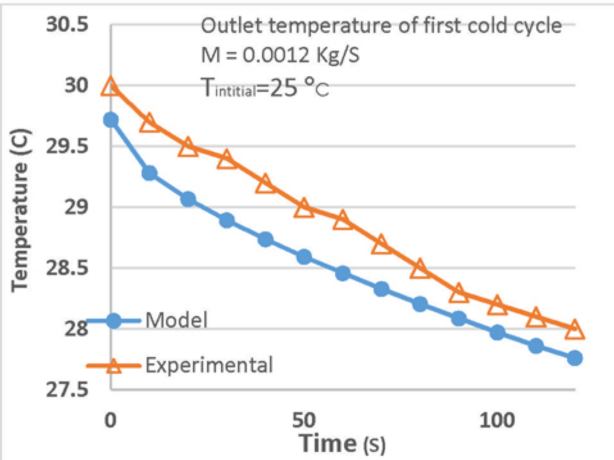

Figure 4. Outlet temperature of first cold period for 15 mm ball

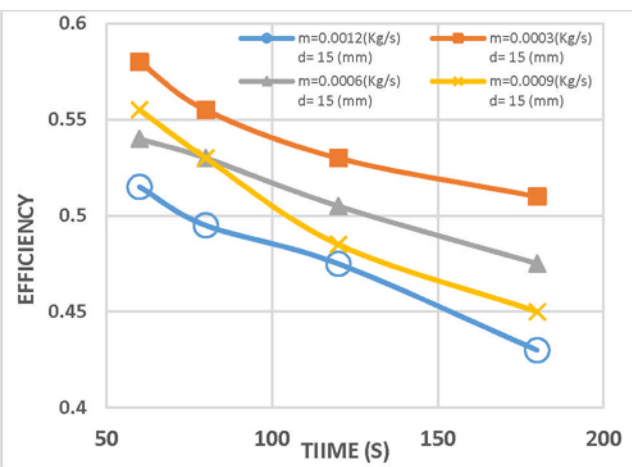

Figure 5. Effect of period time on the regenerator efficiency

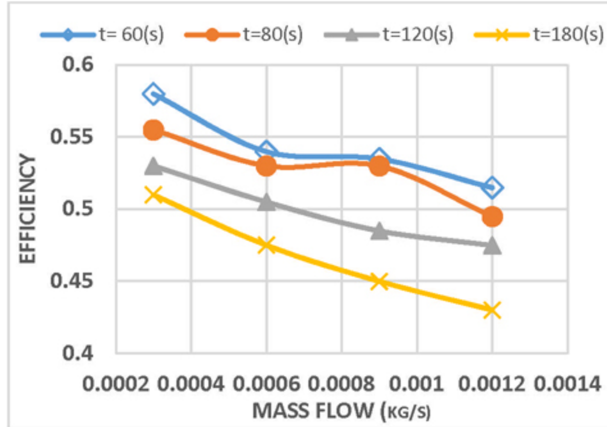

Fig 6. Effect of gas mass flow of on the regenerator efficiency

Figures (5) and (6) show the effect of period time and gas flow rate on the regenerator performance. As shown in the figures the efficiency decreases when period time and gas flow rates increase. This is due to the fact that at higher period times the solid heat capacity of the regenerator decreases and causes the fall of the efficiency. At higher flow rates the residence time of the gas increases and does not allow enough time for the gas to absorb the heat from the packing inside the regenerator.

Effect of ball diameter size

Experiments were done for 2 different diameters of 8 and 15 mm and the results are shown in Figure (7).

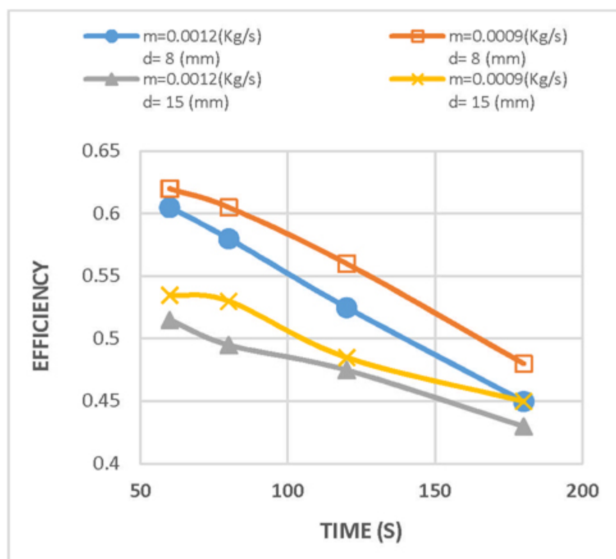

Figure 7. Effect of ball diameter size on the efficiency

As shown in Figure (7) with decreasing of the ball diameter, the efficiency of the system increases. This is due to the fact that at lower ball diameter the heat transfer area per unit volume of the packing is higher and also the pressure drop is increased. Both effects cause an increase in heat transfer coefficient and as a result and increase in the system efficiency.

Conclusions

Energy crisis and environmental issues are the most important problems of the world. For optimizing of the consumption of thermal energy, several devices and instruments have been studied, designed and manufactured in order to improve the recycling of the wasted thermal energy. One of these systems is a fixed-bed regenerator which could have widespread application in aluminum industries to recover the heat from the flue gases and preheat the air for combustion. The operation of such system is periodic. Advantages of this system are larger heat transfer area, uniform distribution of pressure inside the device and no deposits on the packing due to its counter current operation. The most important disadvantages of such systems are that two beds are required in order to have a continuous operation.

The results of this investigation may be concluded as:

- The efficiency of the regenerator has the lowest value when the system operates at symmetric-balanced mode.
- At constant flow of entering gas to the regenerator the efficiency is increased by decreasing the period time.
- The efficiency of the regenerator is increased with decreasing the ball diameter at constant period time and gas flow rate.
- The efficiencies of the cold and hot periods approach each other at cyclic steady state.
- The system can be used very efficiently for the recovery of waste heat from flue gases in melting aluminum furnaces.

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