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Research paper

# Mathematical modelling and simulation of thermal regenerators including solid radial conduction effects

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## HIGHLIGHTS

- A thermal regenerator has been mathematically modelled.
- Two mathematical models have been developed and solved in unsteady conditions.
- An experimental setup has been designed and built.
- Spherical shape packing of different sizes has been used.
- The effect of parameters on the efficiency has been investigated.

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## ABSTRACT

Increasing combustion fuels costs, depletion of fossil fuel reserves, and necessity to control environmental emissions, showing the importance of industrial heat recovery. For this purpose, different types of heat recovery systems have been designed and built. One of the most industrial applicable systems is a thermal regenerator that has widespread applications in energy industries such as glass, aluminium, and power plants. In aluminium and glass melting furnaces such system can be applied to preheat combustion air by absorbing heat from flue gases that results considerable fuel saving in the furnace. Due to the high temperature application of such systems, the packing must be constructed from low conductivity ceramic materials and the mechanism of heat transfer will be convection and radial conduction inside the solids. This paper presents the results of the mathematical modelling and simulation studies of a regenerator filled with spherical shape packing made from alumina with different diameters. For the modelling purposes two mathematical models have been considered; simplest convection model and more complex radial conduction model inside the packing particles. For the 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. Finally, a simulation software package has been developed and used for the prediction of output parameters in two industrial cases and excellent agreement has been obtained that proves the accuracy of the model for the high temperature applications.



## 1. Introduction

Increasing cost of fuels, decreasing of fossil fuel resources and necessity to control environmental pollutions, show the importance of heat recovery systems. Among the most important and energy intensive industries are glass and aluminium industry which have 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. Increasing the efficiency of combustion systems and decreasing of the wastes can be achieved by the design of waste heat recovery systems. Aluminium and glass melting furnaces often have wasted gases with temperatures between 700 and 1000 °C which are suitable resources for heat recovery and

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**Nomenclature**

| | |
|---|---|
| $A$ | heat transfer area, m$^2$ |
| $a$ | heat transfer area per unit volume, m$^{-1}$ |
| Bi | Biot number |
| $C_p$ | specific heat capacity, J/kg K |
| $d$ | packing diameter, m |
| $e$ | grey body emissivity in equation (23) |
| $F_o$ | Fourier number |
| $G$ | mass velocity, kg/s |
| $g$ | gravity |
| $h$ | convective heat transfer coefficient, W/m$^2$ K |
| $h_r$ | radiative heat transfer coefficient defined by equation (23), W/m$^2$ K |
| $k$ | Thermal conductivity, W/m K |
| $L$ | Regenerator length, m |
| $M$ | solid mass, kg |
| Nu | Nusselt number, hd/k |
| $P$ | period, s |
| $P$ | pressure, Pa |
| $R$ | packing radius, m |
| $r$ | radial direction |
| Re | Reynolds number |
| $s$ | Stephan Boltzmann constant in equation (23) |
| $T$ | solid temperature, K |
| $t$ | gas temperature, K |
| $U$ | utilization number |
| $u$ | gas velocity, m/s |
| $x$ | axial distance |
| $y$ | direction normal to the matrix surface |
| $z$ | dimensionless time defined by equation (9) |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | diffusivity coefficient |
| $\beta$ | unbalanced factor |
| $\Delta$ | difference |
| $\varepsilon$ | voidage |
| $\rho$ | density, kg/m$^3$ |
| $\eta$ | effectiveness, % |
| $\Lambda$ | reduced length |
| $\mu$ | dynamic viscosity |
| $\gamma$ | asymmetry factor |
| $\theta$ | time, s |

*Subscripts*

| | |
|---|---|
| $b$ | bulk |
| $c$ | cold |
| $g$ | gas |
| $h$ | hot |
| $i$ | inlet |
| $p$ | packing |
| $r$ | radiation |
| $s$ | solid |

increasing of production efficiency [1]. Among the most important efficient methods in this context is utilization of fixed bed regenerator for recovery of wasted heat from aluminium and glass melting furnaces.

Thermal regenerators are compact heat exchangers, filled with high heat capacity solids, in which heat from the hot gases is absorbed by the solids and will be picked up from the solids by the cold stream which is normally air. They are practically used in two types; fixed-bed (FBR) and rotary. In a fixed-bed regenerator the bed is fixed and the hot and cold streams are periodically passed through the bed as illustrated in Fig. 1 [2], while in the rotary type the stream channels are fixed and the bed, which is called a rotor, periodically rotates and the packing particles are faced with the hot and cold streams. FBRs are mainly used in the glass and aluminium furnaces while the rotary types are mostly used in the power plants and air conditioning systems. One of most important design parameters in regenerators is a high surface area per unit volume of the packing particles [3] called compactness. The regenerator performance is also affected by two more parameters such as inlet gas flow rate and the duration of the periods for the hot and cold streams.

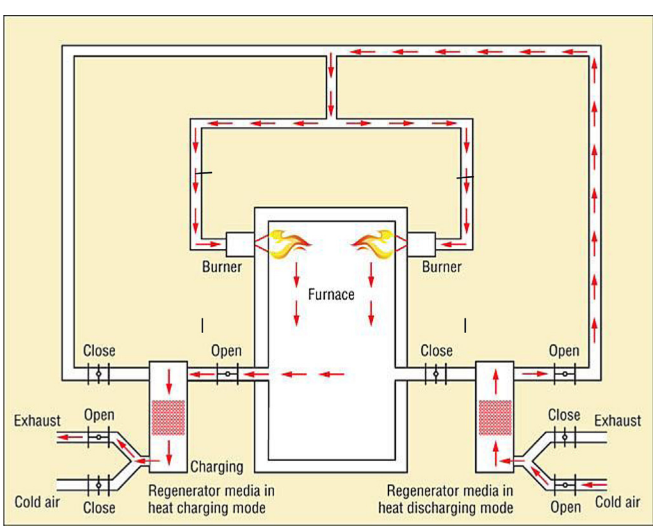


**Fig. 1.** Schematic diagram of a FBR [1].

As mentioned before the operation of a FBR is periodic. In the first period, called hot or charging period, hot flue gases flow through the bed and transfers the heat to the packing. After a certain period time the hot gas flow is stopped and the cold air flow is then passed through the bed countercurrently, absorbs the heat from the packing and is preheated (cold or discharge period). 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 follows:

1 Only one set of flow channel is needed for entry of hot and cold gases inside the system.
2 High heat transfer area exists per unit volume.
3 An even pressure distribution within regenerator system.
4 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.

Requirement of two channels for a continuous operation which results more equipment and maintenance costs for the valves are among the drawbacks of the FBRs.

The simplest mathematical model presented by Nusselt [4] considers convection heat transfer between the fluid and the solid surfaces. Schmidt and Willmott [5,6] developed mathematical

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