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An Experimental Verification of Pressure Drop for Integrated Regenerative Equipment

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New trends in the design of individual pieces of equipment in up-to-date waste-to-energy (WtE) plants especially for low or medium capacity are a gradual decrease in spatial requirements (i.e., a move towards higher compactness) and investment and operating costs together with an increase in the overall effectiveness of the plant. This can only be achieved by the reduction in the number of apparatuses and merging functionally different pieces of equipment into singular units, i.e. by employing so-called integrated equipment.

Our work is focused on the development of a calculation tool for the design of multifunctional unit coupling function of regenerative heat exchanger and flue gas emission cleaning equipment in one apparatus. This paper presents the results of the first stage of our experimental verification focused on the analysis of the selected type of heat transfer surface from hydraulic characteristics point of view. The results show a good match of the calculated pressure drop with the measured data. Therefore, the selected calculation equation can be used for predicting the pressure drop of the packed bed formed by ball particles. The pressure drop courses also show that the significant effect on their value has the correct determination of the porosity.

1. Introduction

Three technological processes typically belong among the key parts of WtE plants, namely (i) thermal treatment of waste; (ii) heat recovery; and (iii) flue gas cleaning (Stehlík, 2016). Regarding it, the design of integrated multifunctional equipment is currently typically focused on the coupling of these individual functionalities. We are focused on the development of a calculation tool for the design of multifunctional unit coupling function of regenerative heat exchanger and flue gas emission cleaning equipment in one apparatus. Such an apparatus can be effectively employed, for example, at the cold end of WtE, as equipment for flue gas heat recovery and together as flue gas cleaning equipment. Involving such multifunctional integrated apparatus will allow the plant to substantially decrease the spatial requirements and investment and operating costs together with an increase of overall effectiveness of the whole WtE plant, as present Jegla et al. (2017). The situation is schematically presented in Figure 1.

A key part of such integrated regeneration equipment is a fixed bed, in which, in addition to thermal accumulation, a chemical reaction (catalytic flue gas cleaning) takes place during the operation of the equipment. At the same time, this equipment must be operated as two identical apparatuses (two beds) operating cyclically – the one is for the accumulation of the heat from the flue gas and the second utilize of the accumulated heat for the catalytic reaction in order to the cleaning of the waste gas. The equipment can also be implemented in the basic design when such a structure can only be used for heating and cooling, so the equipment operates "only" as an efficient regenerative heat exchanger (using heat from the exhaust gas up to its rainy point). Our intention is, however, to design a full-featured multifunctional integrated equipment which part is a catalytic bed allowing simultaneous accumulation of heat and flue gas cleaning. Such integrated equipment can make a significant contribution to reducing WtE spatial, investment and other demands as mentioned above. However, a suitable computational tool is not yet available for the computational design of such multifunctional integrated equipment. Our continuous development activities are focused on a proper and reliable design method for calculation of these multifunctional apparatuses.

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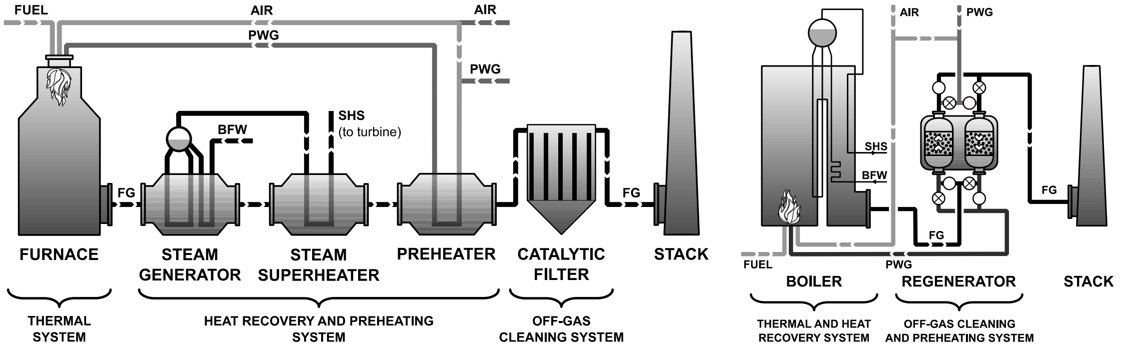


a) Conventional WtE process for thermal treatment of process waste gas (PWG)

b) The same WtE process employing integrated multifunctional apparatus

Figure 1: Scheme of an industrial WtE unit for thermal treatment of process waste gas (PWG) in the conventional arrangement and in an arrangement employing integrated multifunctional equipment – acc. to Jegla et al. (2017)

Within our mentioned development activities, we want to present in this paper the results of the first stage of our experimental verification of pressure drop calculations for employing in our design tool for integrated regenerative equipment. This first stage of experimental verification is focused on influence analysis of selected heat transfer surface type from hydraulic characteristics point of view to confirmation and improvement accuracy of the developed calculation model.

2. Design of regenerative heat exchangers

Regenerators can be defined as specific compact heat exchangers in which heat is alternately stored in and removed from a heat storage material (packed bed). The important advantage of regenerators over recuperators is that they have a much higher surface area for a given volume. Generally, regenerators can be divided into two groups: fixed-bed and rotary (Hewitt, 1998).

This research paper focuses only on fixed-bed one. Some heat storage elements for the fixed bed regenerators (typical elements are shown in Figure 2) have partial self-cleaning capability reducing fouling and corrosion. Regenerators are thus ideal for gas-gas heat exchange as waste heat recovery systems or to simultaneous usage as both heat exchangers and reactors where cleaning of waste can take place (Kilkovský and Jegla, 2016).

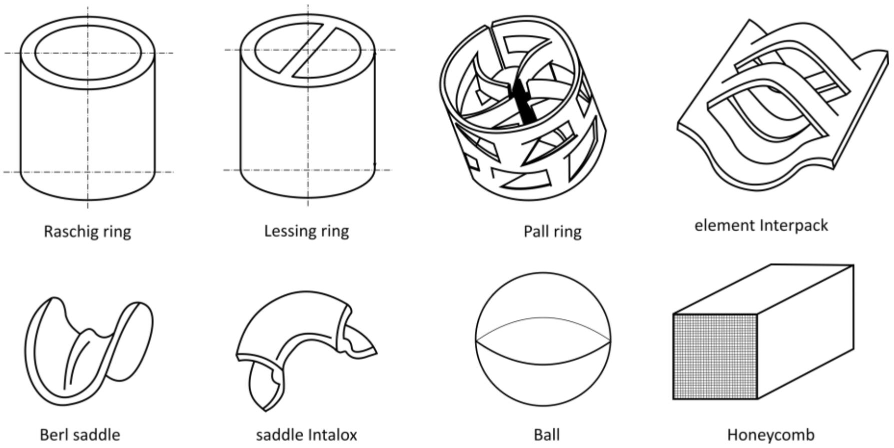


Figure 2: Different types of elements that can form a packed bed

Accurate calculation methods for the design of this equipment involve (due to its time-dependent heat transfer behaviour) differential equations and can be generally classified into two groups: open and closed (Hewitt, 1998). In open methods, the gas and solid temperatures are evaluated by solving the differential equations over successive cycles of regenerator operation. On the other hand, in closed methods, the steady-state performance is calculated directly without considering any previous cycles. Each of these two groups then comprises two subgroups, namely linear and non-linear methods according to the way in which thermo-physical properties are calculated for the gas and the storage material. Our calculation system is based mainly on the open methods, in which the cyclic behaviours of the twin regenerator arrangement are simulated iteratively. Willmott (1964) method is the basis of the linear model, while the Willmott (1968) method is the suitable model for the non-linear system. In both these methods, differential equations are replaced by finite difference formulae obtained using the trapezoidal rule.

Important tasks are finding suitable equations for calculation of the heat transfer coefficient and friction coefficient. Heat transfer coefficient should include the effect of both convection and radiation heat transfer because of potentially high temperatures of gas. These coefficients depend predominantly on the type of storage material. It means that for various types of storage material should be using a special/suitable type of equation for calculation of these coefficients. The respective equations for convective heat transfer were published by Sadrameli and Heggs (1997) while for radiative heat transfer were discussed by Narayanan and Pramanick (2014). Pressure drop in the packed bed is commonly calculated using the Ergun equation (Ergun, 1952). However, this equation very often over-predicts the respective value and thus, it is recommended to use methods tailored to specific storage materials which are based on experimental data (Allen et al., 2013).

3. Methods for pressure drop calculation

The investigation carried out so far indicate that for calculation of the pressure drop are important except the velocity and the physical properties of the fluid also the parameters of the bed. These ones are expressed by a specific surface, characteristic particle size and shape, sphericity, porosity (void fraction) and a ratio between the height of the packed bed and the diameter of the particles. The most well-known relationships for porosity calculation of random packing are the equations proposed by Zou and Yu (1995) and recommended by Di Felice and Gibilaro (2004), in the form:

$$\varepsilon = \varepsilon_b + 0.01\left[exp\left(\frac{10.686}{D/d_p}\right) - 1\right] \qquad D/d_p \ \leq 0.256 \tag{1}$$

where D is the inner shell diameter of the regenerator (m), d_p is the particle diameter (m) and ε_b is the bed porosity (void fraction) in the bulk zone (-).

Zou and Yu (1995) proposed the porosity coefficient $\varepsilon_b = 0.4$ by analyzing the experimental data from the literature, while according to (Ribeiro et al., 2010) the value $\varepsilon_b = 0.373$ is more suitable, which is a value derived from their own data.

Benyahia and O’Neill (2005) created a correlation based on measured data for the spherical particle:

$$\varepsilon = 0.390 + \frac{1.740}{\left(D/d_p + 1.140\right)^2} \tag{2}$$

In the literature, many relations can be found for calculation of the pressure drop (or friction coefficients) through the bed. One of the most well-known equation for calculation of the pressure drop (friction coefficient) of fluid through the bed, was published 60 y ago by Ergun (1952), can be written in the form:

$$f_{p,Erg} = \frac{-\Delta P \ d_p}{L\rho V^2} = \left(150 + 1.75\left(\frac{Re}{1-\varepsilon}\right)\right)\frac{(1-\varepsilon)^2}{\varepsilon^3 Re} \tag{3}$$

in which Re is Reynolds number (-), Δp is the pressure drop (Pa), L is the height of the bed (m), ρ is the fluid density (kg.m^{-3}) and V is the fluid velocity (m.s^{-1}) based on the empty cross-section of the bed. The validity of this relationship is for the range 1 < $Re/(1-\varepsilon)$ < 2300. The relationship gives a higher pressure loss than in reality if $Re/(1-\varepsilon)$ > 700.

The relationship is not exclusively based on the pressure drop across the packed bed with spherical or smooth particles. Tables and charts in Ergun's articles (Ergun, 1952) state that spherical particles, pulverized coke/coal, sand, cylinders and tablets have been used.

However, the recommended coefficients of 150 and 1.75 are questionable. These coefficients are referred to as inappropriate in some papers, and other values are proposed. For example, Hicks (1970) states that these two coefficients should not be constant values but should be a function of the Reynolds number. He also noted that although this equation is recommended in many books as modern and without any limitations, it should not be used for spherical particles if $Re/(1-\varepsilon_b)$ > 500. Handly and Heggs (1968) also founded that Ergun’s equation is not applicable for determining the pressure drop of a bed filled with irregular spherical, cylindrical, annular or flat particles.

According to (Allen et al., 2013) the Ergun equation for *Re* > 700 gives a higher pressure drop for the randomly packed beds of smooth spheres. On the other hand, the measurements made by Zavattoni et al. (2011) for the stone bed was 10-30 % higher than the value given by the Ergun equation.

Other correlations applicable to spherical and non-spherical particles are described below. Their selection includes the most recent relationships and older ones, which, according to (Erdim et al., 2015) show the best accuracy. These selected correlations, which will be a part of our own calculation tool, are compared in the next chapter of this paper with measured values for the bed test.

The first proven correlation is, according to Carman (1937):

$$f_{p,Carman} = \frac{-\Delta P\, d_p}{L\rho V^2} = \left(180 + 2.871\left(\frac{Re}{1-\varepsilon}\right)^{0.9}\right)\frac{(1-\varepsilon)^2}{\varepsilon^3 Re} \tag{4}$$

The second chosen equation is, according to Brauer (1971):

$$f_{p,Brauer} = \frac{-\Delta P\, d_p}{L\rho V^2} = \left(160 + 3.1\left(\frac{Re}{1-\varepsilon}\right)^{0.9}\right)\frac{(1-\varepsilon)^2}{\varepsilon^3 Re} \tag{5}$$

Di Felice and Gibilaro (2004) recommend the model which uses the Ergun's equation for which the porosity is given from Eq(1) with the coefficient ε_b = 0.373 and uses the following relation for the calculation of a bulk zone velocity V_b:

$$\mathrm{V_b} = \frac{\mathrm{V}}{2.06 - 1.06\left(\frac{(D/d_p)-1}{(D/d_p)}\right)^2} \tag{6}$$

The last chosen equation is then, according to Erdim et al. (2015):

$$f_{p,Erdim} = \frac{-\Delta P\, d_p}{L\rho V^2} = \left(160 + 2.81\left(\frac{Re}{1-\varepsilon}\right)^{0.904}\right)\frac{(1-\varepsilon)^2}{\varepsilon^3 Re} \tag{7}$$

4. Experimental determination of pressure drop

Within the research of regenerative heat exchangers and verification of the accuracy of the available calculation equations for the determination of the pressure drop the measurements of some types of materials forming the regenerative bed for different fluid flow rates (7 - 50 m^3/h) were performed. Because the spatial limitations of this paper the pressure drops only are introduced for packed bed formed by ball particles of various diameter. To measure the pressure drop, we used the test apparatus located in our institute described, for example, in (Brummer et al., 2013). This equipment allows the results of measured pressure drops to be automatically stored in the PC. The measuring circuit has a measurement error of up to 0.5 %.

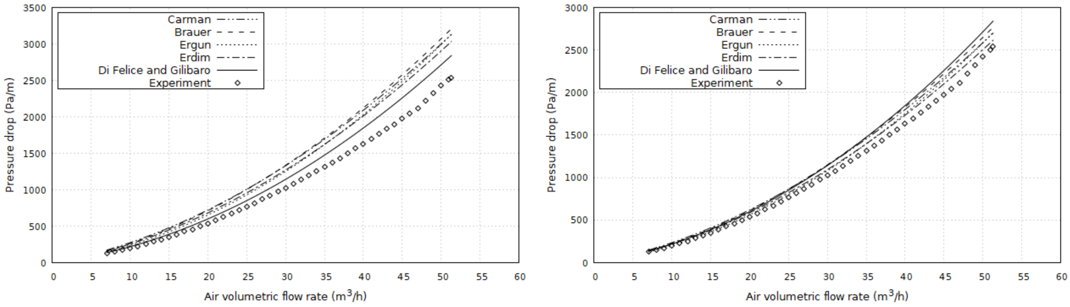
The material formed the bed was placed on a sieve inside a square 150x150 mm tube. The height of the bed was different for various diameters and was designed to cover as much as possible the measuring range of the differential pressure sensor. The pressure drop of the sieve was also determined and subsequently subtracted from the total measured pressure drop of the bed. The used ball particles are from RASCHIG GMBH, whose properties are shown in Table 1.

Table 1: Geometric characteristic of ball particles (RASCHIG GMBH)

Ball-Ø inch	Weight kg/m^3	Pieces $1/m^3$	Surface Area m^2/m^3	Void Fraction, %	
				Zou and Yu (1995)	Benyahia and O'Neill (2005)
1/8	1,400	8,000,000	1,285	37.6	39.1
1/4	1,400	4,750,000	500	37.9	39.3
3/8	1,400	1,140,000	350	38.2	39.5

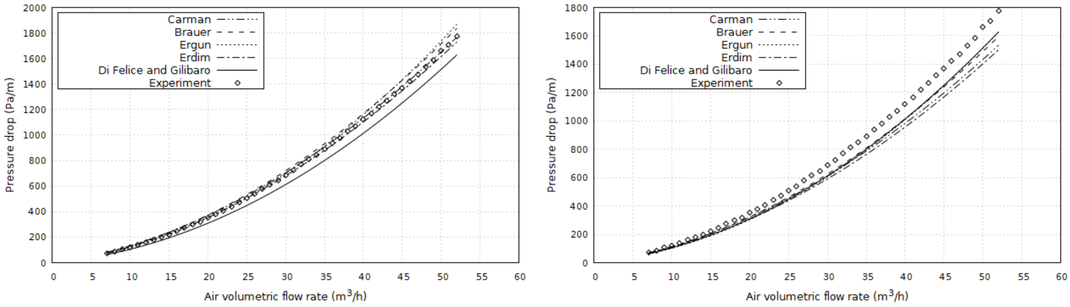
The comparisons of measured and calculated pressure drops for the porosity given by two different approaches (see Table 1) are shown in Figure 3 - 5.

As shown in Figure 3, Figure 4 and Figure 5, a good match of the calculated pressure drop and the measured data is achieved. Therefore, the selected calculation equations can be used for predicting the pressure drop of the packed bed formed by ball particles in the computational software. The results also showed that even a small change in the porosity has a great effect on the calculated pressure drop. If no data is available from the manufacturer, it seems appropriate to use the average value of the porosity from the recommended calculation relationships.



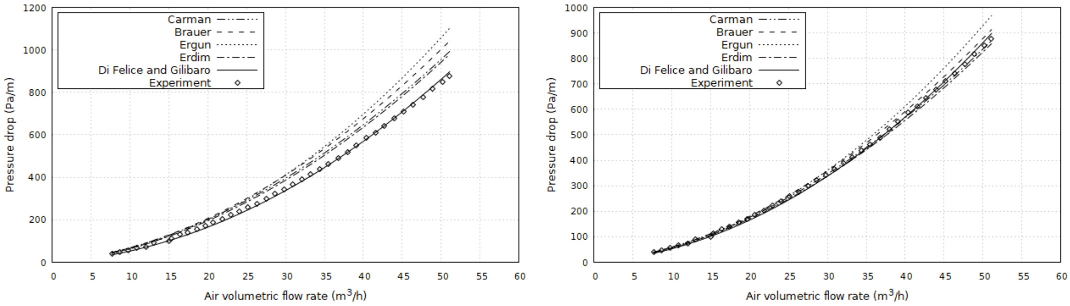
a) Porosity according to Zou and Yu (1995) b) Porosity according to Benyahia and O'Neill (2005)

Figure 3: Comparison of measured pressure drop with pressure drop according to various correlations for randomly packed bed formed by the spheres (1/8 inch).



a) Porosity according to Zou and Yu (1995) b) Porosity according to Benyahia and O'Neill (2005)

Figure 4: Comparison of measured pressure drop with pressure drop according to various correlations for randomly packed bed formed by the spheres (1/4 inch).



a) Porosity according to Zou and Yu (1995) b) Porosity according to Benyahia and O'Neill (2005)

Figure 5: Comparison of measured pressure drop with pressure drop according to various correlations for randomly packed bed formed by the spheres (3/8 inch).

5. Conclusions

This paper deals with the selection and experimental verification of suitable calculation correlations for determination of the pressure drop of the fluid across packed bed formed by the ball particles. The comparison of measured and calculated pressure drop data show that selected computational correlations are appropriate

for its sufficiently accurate prediction. The pressure drop courses also show that the significant effect on their value has the correct determination of the porosity. Even a small change in its value greatly affects the resulting magnitude of the pressure drop. The used computational relationships are suitable for design (or rating) and will be implemented into the created computational software for the design of regenerative heat exchangers.
Currently, the research activity of the second stage of experimental pressure drop verification is finalized. This activity concentrates on the packed bed of non-spherical and layer-oriented elements. The results of this second step of the experimental verification will be subsequently published. The related research activity then is focusing on completing own computational tool and expanding its possibilities for a second function, i.e. the use of the regenerative heat exchanger as a reactor, it means that a catalytic bed will be a part of the regenerator on which reactions will take place in order to reduce the volatile organic matter content in the flue gas.

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