The Dynamic Behavior of Water Flowing Through Packed Bed of Different Particle Shapes and Sizes

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ABSTRACT

An experimental study was conducted on pressure drop of water flow through vertical cylindrical packed beds in turbulent region and the influence of the operating parameters on its behavior. The bed packing was made of spherical and non-spherical particles (spheres, Rasching rings and intalox saddle) with aspect ratio range 3.46 < D/dp < 8.486 obtaining bed porosities 0.396< ε <0.84 and Reynolds number 1217< Re_p < 21758. The system is consisted of 5 cm inside diameter Perspex column, 50 cm long; distilled water was pumped through the bed with flow rate 875, 1000, 1125, 1250,1375 and 1500 l/h and inlet water temperature 20, 30, 40 and 50 ˚C. The packed bed system was monitored by using LabVIEW program, were the results have been obtained from Data Acquisition Adaptor (DAQ).

Key words: pressure drop, packed bed, Ergun equation, friction factor, power consumption.

السلوك الديناميكي للماء اثناء جريانه خلال عمود محشولجسيمات مختلفة الاشكال والاحجام

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الخلاصة

تم اجراء دراسة عملية لحساب هبوط الضغط للماء خلال جريانه في وسط عمودي أسطواني محشو ضمن المرحلة المضطربة في ظروف تشغيلية مختلفة تتضمن حشوات ذات اشكال كروية وغير كروية (spheres, Rasching rings and intalox saddle) ذات تعبئة عشوائية وبمعدل $3.46 < D/dp < 8.486$ ومسامية $0.396 < \varepsilon < 0.84$ وعدد رينولد $1217 <$ $Re_p < 21758$. يتكون العمود من أنبوب من الزجاج ذو قطر5 سم وطول 50 سم معبئ بحشوة وقد تم ضخ ماء مقطر خلال العمود في ظروف مختبرية مختلفة تتضمن معدلات تدفق (875, 1000, 1125, 1250,1375 1500 l/h) ودرجات حرارة ابتدائية للماء (20, 30, 40 and 50 ˚C). تم استخدام برنامج LabVIEW لاستحصال النتائج المختبرية خلال جهاز اكتساب البيانات (DAQ).

الكلمات الرئيسية: هبوط الضغط، عمود محشو، معادلة Ergun، عامل الاحتكاك، استهلاك الطاقة.

1. INTRODUCTION

In several chemical engineering requests such as separation columns, chemical reactors and heat exchangers, the fluid flowing through fixed beds are very important. It is frequently attached by complex phenomena such as heat and mass transfer**, Rong, et al., 2014**. In order to find best design and control of the complicated fluid–particle flow system, it has been recognised that it is necessary to understand the basics**, Rong, et al., 2013**. Liquid flow through a packed bed of solid particles is applicable to many industrial operations, which include the transfer and storage of thermal energy, drying and heterogeneous catalytic reactions**, Sarmad,** and **Safa, 2015**. For obtaining fast heat and mass transfer, chemical engineering processes usually include the use of packed columns, because these devices have a large surface area to volume ratio for contact between a gas and a liquid such as absorption or a solid and a liquid or gas like catalysis**, McCabe, et al., 2005, Perry, 2008**. In early years, in order to minimize large exploitation and maximize factory execution, industry operations are facing challenges. So, the simulation and process modelling play a main role to support the optimum design and operation of the process equipment. Studies on the achievement of packed bed columns with respect to the understanding of physical procedures involved through process modelling have been subjects of attention of researchers**, Jameson, et al., 2015**.

An important industrial problem that concerns several fields of chemical engineering is the dispersion of mechanical energy in the flow across porous media**, Comiti,** and **Renaud, 1989**.

The pressure drop through a packed bed must be known in order to estimate the capital and operating costs and to size the blowers or pumps required to force fluid through it**, Allen, et al., 2013**. The pressure drop across fixed beds is of main importance for the design of packed bed reactors, since it defines the energy requirements of the supplying pumps and compressors, and this directly correlates to how much the apparatus will cost to run and to preserve the optimal operating conditions and to maximize the product**, Eisfeld,** and **Schnitzlein, 2001**. The main purposes of this work are to design, construct and install a laboratory rig for measuring the pressure drop for different types and sizes of packing., studying different parameters affecting the pressure drop of water flow and the bed friction factor through packed bed such as flow rate, type of packing, packing height, inlet temperature and wall effect (D/d_p) and calculating the parameters of packed bed characterization (particle friction factor, drag force and power consumption).

2. THEORY

The pressure drop is the change in pressure between two points of a fluid, occurs when frictional forces, due to the resistance to flow, act on a fluid as it flows through the porous media and fluid viscosity. Pressure drop increases by increasing the frictional shear forces. After decades of intensive research, it is generally accepted that the pressure drop can be calculated by simple, semi empirical models like the Ergun equation in a satisfactory way, at the limit of an infinitely expanded packed bed**, Winterberg,** and **Tsotsas, 2000**. The rate of momentum transfers from the fluid to the solid particles therefore; the pressure drop for flow through the bed is related to the physical mechanisms by which flow occurs. The pressure drop over a range of Re_p that comprises laminar and turbulent flow regimes may be considered to be the sum of following two classes: firstly, proportional to fluid velocity, that is caused by viscous resistance at the walls of the pore, secondly, proportional to the square of the fluid velocity, that is attributable to inertial resistance, additionally to kinetic energy losses caused by direction change**, Comiti,** and **Renaud, 1989**.

For calculating pressure drop Ergun equation is the general equation valid for laminar, turbulent as well as transitional region**, Geankoplis, 2008**:

$$\Delta P = \frac{150\,\mu_f\,u_s\,L}{\emptyset^2\,{d_p}^2}\frac{(1-\varepsilon)^2}{\varepsilon^3} + \frac{1.75\,\rho_f\,{u_s}^2 L}{\emptyset\,d_p}\frac{(1-\varepsilon)}{\varepsilon^3} \tag{1}$$

The first term gives the Blake-Kozony equation for laminar flow (viscous energy loss), void fractions less than 0.5 and $Re_p < 10$, the second term Burke – Plummer equation for highly turbulent flow (inertial energy loss), for $Re_p > 1000$.

The coefficients 150 and 1.75 in the Ergun equation are depend on the Reynolds number, particle shape and bed porosity. The average interstitial velocity in the bed is u (m/s) and it is related to the superficial velocity based on the cross section area of the empty container as follows:

$$u_s = u\varepsilon \tag{2}$$

Since the particle diameter can be defined as**, McCabe, et al.,2005**:

$$d_p = \frac{6\,(1-\varepsilon)}{\emptyset\, a} \tag{3}$$

for a sphere ∅ = 1, and for non-spherical particles 0 < ∅ < 1**, Koekemoer,** and **Luckos, 2015**:

$$\emptyset = \frac{surface\ area\ of\ sphere}{surface\ area\ of\ particle} = \left[\frac{36\pi {v_p}^2}{{s_p}^3}\right]^{1/3} \tag{4}$$

$$a = a_v(1-\varepsilon) = \frac{6}{d_p}(1-\varepsilon) \tag{5}$$

In fixed beds, the flow is considered laminar when the Reynolds number is less than 10 and turbulent when the Reynolds number is greater than 1000. For packed beds, the Reynolds number defined as follows:

$$Re_p = \frac{\rho_f\, d_p u_s}{(1-\varepsilon)\, \mu_f} \tag{6}$$

The pressure drop in a packed bed is typically estimated by using Ergun equation with an appropriate correlation for the friction factor**, Harrison, et al., 2013**:

$$f_p = \frac{\Delta P\, d_p\, \varepsilon^3}{L\, \rho(1-\varepsilon)\, {u_s}^2} = \frac{150}{Re_p} + 1.75 \tag{7}$$

The friction factor in laminar regime is only affected by Re_p while in turbulent regime, where high of Re_p, it depends only on particles roughness**, Bird, et al., 2002**.The viscous friction at the wall increases the pressure drop, may not be negligible in comparison to that produced by particles due to the fact that friction of the wall increases relative to the total bed surface reliable to particles as the bed-to-particle diameter ratio $\left(D/d_p\right)$ decreases**, Koekemoer,** and **Luckos, 2015**.

2.1 Velocity Distribution

One of the fundamental factors in the study of packed bed systems is the velocity distribution of the flowing fluid across the bed**, Subagyo, 1997**. When the packing construction is fixed three zones can be recognised**, Rong, et al., 2013**:

- A low-velocity zone surrounding particle surfaces.
- A high-velocity zone near the centre of stenosis of pores.
- A recirculation zone with negative velocities in the wakes of leading particles.

The assumption of homogeneous water inlet velocity and porosity bed distributions across a bed cannot be factual near the tube wall, where the solid particles have to arrange themselves differently, close to the wall the void fraction so, the water velocity will tend to be larger than in the bulk region. The superficial velocity of water u_s divides between the bulk region and the wall region according to**, Felice,** and **Gibilaro, 2004**.

$$u_s = \left[\frac{(D/d_p)-1}{(D/d_p)}\right]^2 u_b + \left[1-\left(\frac{(D/d_p)-1}{(D/d_p)}\right)\right]^2 u_w \quad (8)$$

Eq. (10) used to evaluate the bulk zone u_b from the total superficial velocity u_s as a function solely of the bed/particle diameter ratio D/dp under all flow conditions:

$$u_b = \frac{u_s}{2.06-1.06\left(\frac{(D/d_p)-1}{D/d_p}\right)^2} \quad (9)$$

Energy losses or friction losses refer to the difference in pressure needed to overcome the pressure drop during flow through tubes or packed bed. The losses only occur as a result of dynamic movement caused by flow, the pressure difference associated with this process is referred to as the dynamic differential pressure. Friction losses can only occur when flow takes place. The power consumption (P) can be calculated from the following equation**, Barbour, 1995**:

$$P = \frac{\Delta P\ Q}{\varepsilon} \quad (10)$$

The total rate of energy losses may be related to both the general pressure drop and the total drag force on all the particles such that**, Foscolo, et al., 1983**:

$$\Delta P = \frac{F_D}{A\ \varepsilon} \quad (11)$$

3. EXPERIMENTAL WORK

The experimental setup was prepared for measuring the pressure drop along the bed by using NI LabVIEW program under different ranges of experimental conditions including water flow rates (875, 1000, 1125, 1250, 1375 and 1500 l/h), inlet water temperature (20, 30, 40 and 50 ^oC), different shapes and sizes of packing. Before the experimental work the bed porosity was measured following the standard experimental procedure for determining the porosity of different shapes and sizes of packing. The pressure across the bed was measured by using pressure sensors which connected between them in parallel to the Data Acquisition Adaptor (DAQ). The results have been obtained from Data Acquisition Adaptor (DAQ) device known as NI-Arduino type 2560, six pressure sensors were inserted in the packed bed column axially 10 cm a part each other responsible for sensing the pressure from their positions on a bed.

The experimental rig which was used for performing the present work is shown in **Fig. 1**. The experimental apparatus was consisted of six pressure sensors with input pressure 0-15 psi→output voltage 0.5 - 4.5V, with accuracy 1.5 % of reading to measure the pressure along the bed, different types of packing, Perspex glass column (5 cm I.D, 5.5 cm O.D with a length of 50 cm) that holds the particles, holder of packing to keep the bed in position, pump to circulate the water to the test section, different valves to control the volumetric flow rate of water, rotameter to get the desired flow rate, water reservoir and temperature controller to control the water reservoir temperature.

4. RESULTS AND DISSCUSION

The effect of many operating parameters with different ranges (inlet temperature 20, 30, 40 and 50 ^oC, flow rate 875, 1000, 1125, 1250, 1375 and 1500 l/h, aspect ratio 4.46, 5, 5.456, 6.25, 7.7, 8.333, 8.486, bed porosity 0.396, 0.407, 0.415, 0.6, 0.68, 0.7 and 0.84) on the pressure drop will be discussed to understand and interpret.

Three types of packing were used and their specifications are tabulated in table (1).

The effect of water inlet temperature on the pressure drop illustrates in **Fig. 2**. It can be noticed that the pressure drop is decreasing by increasing the water inlet temperature for all types of packing, this may be attributed to the fact that when the temperature increases, the viscosity and density of the water decreases so, the viscous friction (frictional forces) between the layers of water will decrease.

Fig. 3 shows the effect of flow rate on the pressure drop at constant temperature. It can be seen that increasing flow rate leads to increase the pressure drop. This can be ascribed to existence of the eddy currents that react with each other which cause increasing in drag force or resistance to flow and that is in a good agreement with**, Oyinkepreye, et al., 2012**.

As a general rule, decreasing the average porosity of the bed thereby, increases the pressure drop across it as shown in **Fig. 4.** This is caused by decreasing in the particle diameter which results decreasing in the void fraction between particles causes a significantly decreasing in permeability of the bed and increasing the resistance to flow and that is in a good agreement with**, Ribeiro, et al., 2010**.

Fig. 5 shows the effect of aspect ratio on the pressure drop at constant inlet temperature It is evident that decreasing the bed-to-particle diameter ratio i.e. increasing the wall effect causes decreasing in the pressure drop because existence of larger channels near the wall regions than those formed between particles Thus, in a bed of large-size particles provides a lower pressure drop and that is in a good agreement with**, Nemec,** and **Levec, 2005, Montillet, et al., 2007.**

Fig. 6 shows the pressure drop along the bed at constant inlet temperature. It can be observed that for all inlet temperatures whenever the packed bed height increases, the water flow resistance increases this leads to increase in pressure drop.

The power consumption usually decreasing when the diameter of particle increasing. The reason for this behavior is that by increasing of average bed porosity and decreasing the resistance to flow of the water leads to decrease the pressure drop as shown in **Fig. 7.**

Fig. 8 demonstrates the comparison of experimental results of pressure drop with previous workers for flow through column packed with spheres, Ergun equation overpredict the experimental data for the reason that Ergun equation does not take into account the wall effect on pressure drop where ($/dp >$ 10) (i.e. diameter of the particle is very close to that of the column) and that is in a good agreement with**, Nemec,** and **Levec, 2005**. So, for large aspect ratio ($D/dp =$ 8.33) the percentage from Ergun at four inlet temperature was 11% ,while for ($D/dp =$ 6.25, 5) the average deviation was 15 and 16% respectively. Therefore, the average deviation from Ergun prediction was decreasing as the aspect ratio increasing.

For non-spherical particles, Ergun equation was underpredicted the experimental results as shown in **Fig. 9** and **10**, where for Rasching ring with average deviations 29, 31 and 59 % for the bed-to-particle diameter ratio (D/dp) = 8.48, 7.7 and 5.45,while for irregular shape with D/dp= 4.46, the average deviation was 29.3 % for the reason that Ergun equation is mainly applicable for average bed porosity range of $0.35 < \varepsilon < 0.55$, where Ergun equation included pressure drop measurements for flow through beds packed with various sized spheres, cylindricals, sand and crushed materials**, Nemec, and Levec, 2005, Kang, 2010**.

5. CONCLUSIONS

1) The pressure drop of the water across the bed increases when both the inlet water flow rate and the aspect ratio (D/dp) increase.
2) The pressure drop across bed increases as the packing height increases.
3) The bed porosity highly affects the pressure drop and inversely proportional to it, while increasing the porosity causes increasing in particle friction factor.
4) The pressure drop across bed increases as the packing height increases.
5) The power consumption increases when the average bed porosity decreases.
6) Ergun equation was always over predicts the experimental results for sphere, while for non-spherical packing, the correlation predicts pressure drop lower than those found experimentally.

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NOMENCLATURE

a = ratio of total surface area to total volume of the bed, m^{-1}

a_v= specific surface area of a particle, dimensionless

D= column diameter, m

d_p= particle diameter, m

F_D= drag force, N
f_p= particle friction factor, dimensionless
L = length of the bed, m
P = power consumption, W
Q = volumetric flow rate, l/h
Re_p particle Reynolds number, dimensionless
S_p = surface area of a particle, m^2
Ti= inlet temperature of water , ^oC
U = average interstitial velocity in the bed, m/s
u_b = average bulk velocity, m/s
u_s = superficial velocity in the bed, m/s
u_w= average Velocity at wall column, m/s
v_p = particle volume, m^3
ε= porosity, dimensionless
$\emptyset$= sphericity, dimensionless
μ_f= fluid viscosity, kg/m^3
ρ_f= fluid density, kg/m^3
ΔP= pressure drop through packed bed, Pa

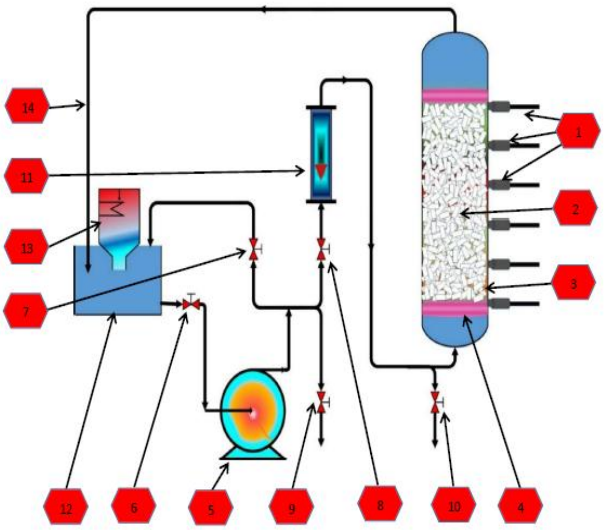

Figure 1. Schematic diagram of experimental setup.

1. Pressure sensors, 2. Packing, 3. Perspex column, 4. Holder of packing, 5. Pump, 6. Main valve (V-1)), 7. By-pass valve (V-2), 8. Rotameter valve (V-3), 9. Drain valve 1 (V-4), 10. Drain valve 2 (V-5), 11. Rotameter, 12. Water reservoir, 13. Temperature controller, 14. Hose.

Table 1. Packed bed parameters.

Type of Packing	dp (mm)	D/dp	Ø	ε
Sphere	6	8.33	1	0.396
	8	6.25	1	0.407
	10	5	1	0.415
Rasching ring	5.8	8.48	0.44	0.6
	6.4	7.7	0.31	0.68
	9.1	5.45	0.2	0.84
Intalox saddle	11.2	4.46	0.3	0.7

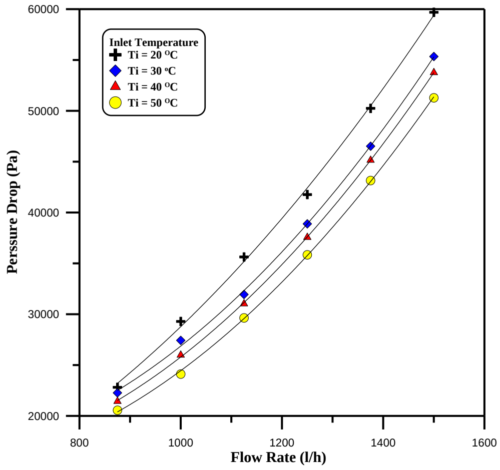

Figure 2. Pressure drop vs. flow rate for sphere at dp = 6 mm.

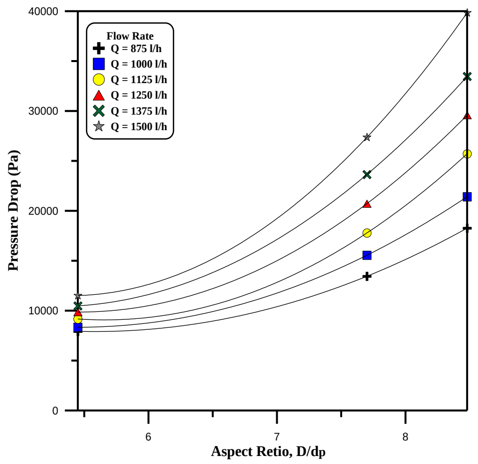

Figure 3. Pressure drop vs. aspect ratio for Rasching ring at Ti =20 ^{o}C.

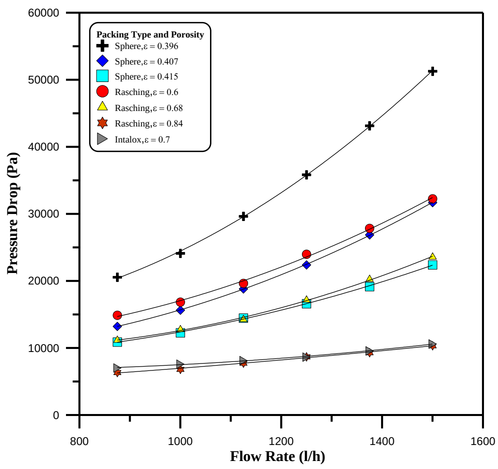

Figure 4. Pressure drop vs. flow rate for different shapes and sizes packing at Ti = 50 ^{o}C.

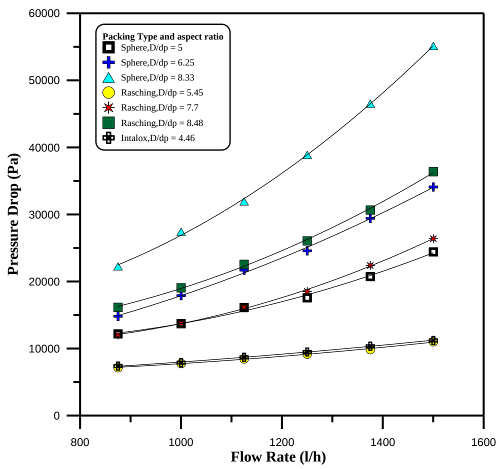

Figure 5. Pressure drop vs. flow rate for different shapes and sizes packing at Ti = 30 ^{o}C.

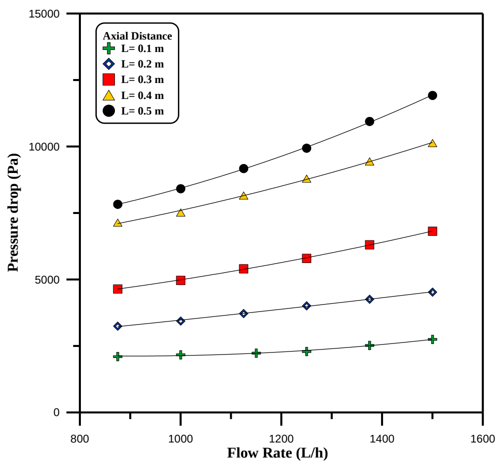

Figure 6. Pressure drop vs. flow rate for intalox saddle at dp=11.2 mm, Ti = 20 ^{o}C.

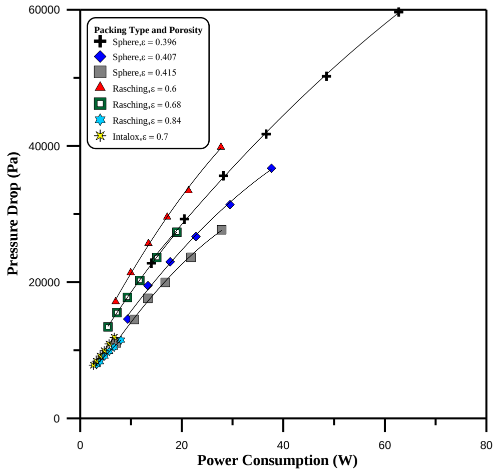

Figure 7. Pressure drop vs. power consumption for different shapes and sizes packing of spheres at Ti = 20 ^{o}C.

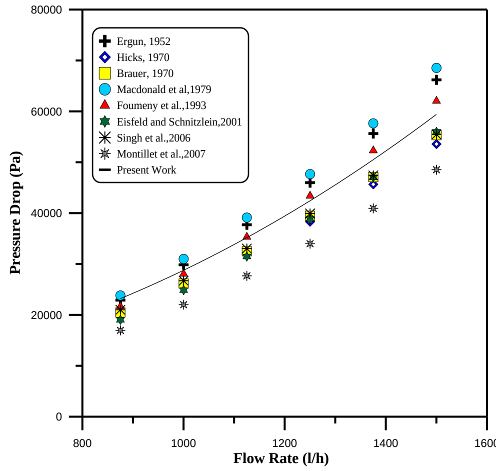

Figure 8. Comparison of present results for sphere with previous workers at dp=6 mm,Ti=20 ^{o}C.

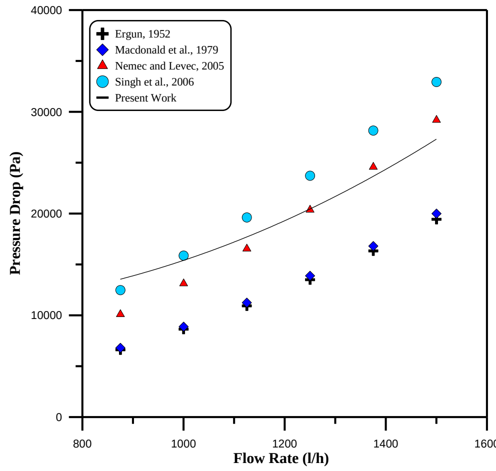

Figure 9. Comparison of present results for Rasching ring with previous workers at dp = 6.4 mm, Ti=20 ^{o}C.

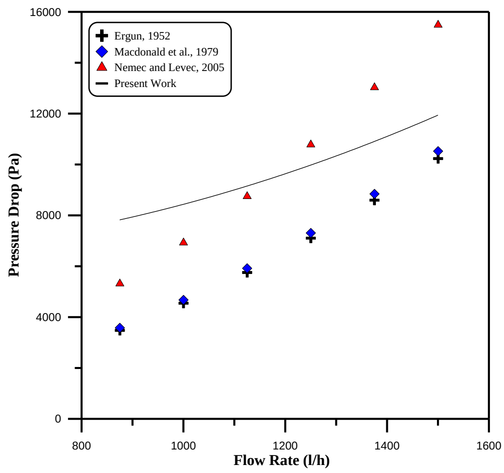

Figure 10. Comparison of present results for intalox saddle with previous workers at dp = 11.2 mm, Ti=20 ^{o}C.

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