Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2022.28296

253 (2022) 166–176
March

Comparative analysis of the hydraulics of columns filled with natural (eco) or waste materials

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Received 1 October 2021; Accepted 14 February 2022

ABSTRACT

The paper presents the results of experimental studies on one- and two-phase flow in packed columns. In the study, natural materials (LECA, pumice stone, cones, coconut fiber, wood chips, walnuts, shells), waste materials (plastic nuts, bricks, tiles), copper springs, and plastic acorns were used as packing. The relationship between the flow resistance coefficient and the Reynolds number is described. In the model, the relationship between the pressure drop on the sprayed packing and the pressure drop on the dry packing is presented. The characteristic values for the studied materials were obtained. The study constitutes the basis for further studies of packings of various origins in order to determine the influence of variable geometrical dimensions.

Keywords: Packed column; Natural materials; Waste materials; Pressure drop

1. Introduction

Due to the development of industry, column apparatuses are widely used all over the world [1,2]. However, characterizing the hydrodynamics of a two-phase flow in packed columns is a difficult task that is constantly being analyzed by many scientists [3,4]. Column devices are an inseparable element of chemical processes such as: absorption, desorption, distillation, rectification, and extraction [5,6]. In the petrochemical and refining industries, columns are the main part of technological installations [7]. The main element of this apparatus is the type of used packing, which affects the quality of the final product. The packing increases the contact surface of phases, which in turn results in the intensification of the mass transfer, and also the improvement of the efficiency of the process. The constant striving to achieve the best possible efficiency of processes has forced the improvement of the structure of packing in order to obtain the largest specific surface area with the lowest possible flow resistance of the medium. This has led to the development of many types and shapes of packings, which all meet different requirements. Research presented by Zhao et al. [8] focused on the improvement of the mass transport efficiency of a packed column by replacing traditional packing with newer types. Three different kinds of packings were tested with

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regards to the absorption of CO_2: super mini rings (SMR), pall rings, and Mellapak. The packings were arranged randomly and had a diameter of 13 mm. It was noticed that the use of SMR increased the mass transfer coefficient by about 20% and 30% when compared to Mellapak and pall rings, respectively. Therefore, it was possible to reduce the height of the column with SMR packing when compared to the other types of fillings. SMR enables higher gas flux values with higher liquid resistances to be used, and this in turn enables better absorption of CO_2. The pressure drops in the case of all the packings were comparable. Fillings, as individual elements, can be piled or stacked, or can even be so-called modular packing. Xu et al. [9] analyzed the influence of the liquid feed temperature, DEEA concentration, lean CO_2 loading, liquid flow rate, CO_2 partial pressure, and inert gas flow in an absorption column equipped with Sulzer DX packing on the mass transfer coefficient. Additionally, a comparison was made with a column filled with Dixon ring packing of the same height and diameter. Based on the obtained results, it was shown that the DEEA concentration, lean CO_2 loading and liquid flow rate have a significant impact on the value of the mass transfer coefficient, while the impact of the inert gas flow was shown to be small. A higher efficiency of CO_2 absorption in the aqueous DEEA solution was observed for a structured packed column when compared to a loosely packed column. Two experimental KGav correlation models for a CO_2-DEEA system were also proposed. Compliance with the results of the experimental studies was high and amounted to 8% and 3%, respectively.

In addition to columns, packings are also applied in devices that are used to purify gases and liquids. Due to the necessity of removing pollutants, or reducing their amount to a minimum, new and better technological solutions are constantly being sought [10]. A lot of research and scientific tests are carried out on the effectiveness of removing harmful compounds through packings that are available on the market, as well as through those of natural origin [11]. A review of literature shows that many innovative solutions are currently being used to improve the processes of mass transfer, heat transfer or separation. For example, Canul Bacab et al. in paper [12] proposed the conducting of the process of anaerobic fermentation in a closed system using packed bed apparatus coupled with an anaerobic sludge blanket. The proposed solution allows for a significant reduction of decomposing organic substances in garbage, and also a reasonably high methane efficiency. In addition, the study attempts to modify the properties of the applied packing, and also to increase the efficiency of the process by using micro-aeration for the packing.

It is worth noting that in some cases natural packing is an excellent replacement for manufactured fillings, and after being used does not pose a problem with regards to disposal. The main apparatuses used for this purpose are biofilters. They are increasingly applied for the elimination of pollutants due to their low cost, low energy demand, uncomplicated process control, and high efficiency of gas purification. The selection of appropriate packing is the key issue that determines the effectiveness of the work of biofilters. Materials of natural origin, such as soil, peat, compost, tree leaves, bark, moss, heather, hay, as well as other materials like plastic or synthetic fittings, are used as biofiltration packings that constitute the substrate for the development of microflora [11,13,14]. In turn, work [15] proposes the use of a combined biofilter in order to increase the efficiency of the waste gas cleaning process from a food industry plant. For this purpose, two types of biofiltration packings were tested: stump and pine bark chips, and also stump, pine bark chips and compost. Effective purification of waste gases by biofiltration can also be ensured using fibrous materials, but only when maintaining optimal conditions and process parameters. Examples of natural fibers used in gas deodorization are jute, hemp and cotton [16]. Peat, the shredded bark of conifers, hay in the form of chaff, and sawdust are the filter media that are used in the processes of reducing the emission of waste gases from livestock housing [17]. Carreño Sayago in paper [18] noted that cellulose is an interesting material for removing heavy metals, and that it can be used in the water treatment process. In his research, the author proposed the use of a biofilter with a biomass of E crassipes transformed with iron for the treatment of water contaminated with Cr(VI). Unlike other biofilters, which are usually filled with an organic medium and which operate with a minimum amount of water, biotrickling filters are almost exclusively filled with inorganic media or solids, over which there is a distinct liquid phase. Biotrickling filtration is one of many promising biological techniques for odour and VOC control [19]. The packing is usually made of an inert material, which can include: plastic fittings, volcanic lava stones, structural plastic fillings, or open-pored synthetic foams. Other materials that are used are glass or rock wool, shredded tires, glass beads, or ceramics.

Loose packings are widely used in mass and heat exchange processes in gaseous and liquid environments. They can be in the form of rings, spheres, cylinders, grains, grates, or spirals. High-performance packing is an effective way to intensify the efficiency and performance of column apparatuses. They reduce pressure drops, electricity consumption and the liquid retention time in the column, thanks to which the process is faster. In order for a filling to fulfill its role well, it must have certain features: a large unit area and porosity, low flow resistance, appropriate resistance to chemical substances, high values of mass transfer coefficients, and – taking into account the economic aspect – it should also be cheap [20].

The authors undertook the study of the hydrodynamics of a column with a loose bed constituting material that had not previously been tested for its suitability as column packing. Natural (eco) material and/or waste material was selected, that is, clay aggregate, pumice stone, shells, cones, acorns, nuts, springs, and pieces of crushed brick and roof tiles.

2. Material and methods

2.1. Aim

The packing elements of the column in which the process takes place should be characterized by the largest possible unit area, high porosity, good wettability, low weight, and low price. However, this is only theory, and it is practically impossible to meet all the assumptions at the same time [20]. When choosing packing, a compromise should be made between all the requirements imposed on these elements, which can be natural (eco) or waste materials (their reuse). The aim of the tests is to determine the drop of pressure in a counter-current flow packed column with regards to the used packing, as well as to determine the gas and liquid flow velocity for a single-phase gas flow and for two-phase gas and water flows. The research covered packings of loose materials, that is, LECA (light expanded clay aggregate), garden pumice stone, shells, black alder cones, larch cones, acorns, plastic nuts, copper prism springs, and pieces of crushed brick and roof tiles. No articles describing the materials used as column fill have been found in the literature. Therefore, it seems advisable to supplement these data, not only for cognitive but also practical/engineering reasons. The main advantage of such packing is that it is cheap and very accessible. Additionally, in many cases the only preparatory process is drying the elements. The surface of such packing can be additionally modified in order to obtain the best possible properties.

2.2. Characteristics of materials

In the conducted research, natural materials (LECA, pumice stone, cones, coconut fiber, wood chips, walnuts, shells), waste materials (plastic nuts, bricks, tiles), as well as copper springs and plastic acorns were used as the packing.

LECA (Fig. 1a) is a lightweight construction aggregate that is made by firing loam clay. Its high porosity makes it a very good filter. It is non-flammable, is resistant to water, chemicals, mold, and fungi, and has good thermal insulation parameters.

The next used natural packings were two fractions of garden pumice, that is, 4–8 mm and 10–20 mm (Fig. 1b). Pumice is a very porous, low-density volcanic igneous rock, which is mainly formed from rhyolite lava. Thanks to these properties, it has become a good filtering and insulating material.

Piemont ceramic tile from Roben Company (Fig. 1c) and clinker brick (Fig. 1d) were also used as a waste material for filling in the column. Ceramic materials in the chemical industry play a key role due to their completely inert character towards harmful chemicals. Apart from their acid- and alkali-resistant properties, they are characterized by very minimal water absorption, which makes them a durable and relatively cheap packing.

Alder chips (Fig. 1e) are subjected to drying treatment at a temperature of approx. 600°C, during which mold and fungus spores, as well as microorganisms, are eliminated from the processed wood mass. They can be used in traditional smokers, smokers with smoke-generators, for grilling, in biofilters [21], and for the removal of pollutants (VOCs) from waste air [22].

The lignified ovate fruits of the alder tree (Fig. 1f), which resemble cones, are of medium size, but definitely smaller in size than larch cones – as can be seen in Fig. 1g. They are initially green, but turn brown over time. The fruits have small, winged seeds that are released when they reach maturity. Alder cones are used to lower the pH of water, and in aquariums they can be used as disinfectants due to their tannin content. Larch and pine cones (Fig. 1g and h) are often used as natural packing in biofiltration processes. They show satisfactory results in the degradation of pollutants. This material is characterized by its oval, elongated shape, and when they ripen they reach 5 cm in the case of larch and 7 cm in the case of pine. Young cones are green in color, and when ripe they are light brown with scales at their edges. The cones drop after releasing their seeds.

Walnuts, or their shells (Fig. 1i), are suitable as filter fillers due to their roughness. They are also suitable for column packings. Walnut shells are recommended as packings in the removal of organic dyes from industrial wastewater [23].

Another natural packing is coconut fiber. These fibers are obtained from ripe coconuts, and are located between the hard shell of the coconut and the outermost layer of flesh. The cells of the coconut fibers are long, hollow, and have a thick cellulose wall. A single coconut fiber is approximately 10–30 cm long. Raw coconut fibers are shown in Fig. 1j. In various industries they can be used as column packing, and in the chemical industry they can also be used for the production of water filters, which can be used in sewage treatment plants and water treatment plants. In addition, filtering installations (in which coconut fibers are used in the first stage of the treatment process, and burnt rice husks in its second-stage) can be used to provide water to the population of poor areas.

The research material also included shells (Fig. 1k) that were collected on a beach in Israel, and which were then divided into two sizes: small and large. The limestone skeleton of the shells is a very delicate material that is sensitive to mechanical damage, but resistant to chemicals and water.

Plastic has now become the dominant material that causes enormous damage to the environment. The lack of unambiguously stated regulations and poor waste management has contributed to significant environmental pollution. Therefore, in order to reuse bottle caps, it was decided to test them as column packing. This waste is produced from pure PET polymer (polyethylene), which is characterized by high corrosion resistance, low abrasion, and very good sliding properties. The collected caps were divided into 2 fractions: with a diameter of 28 and 38 mm (Fig. 1l).

Copper prismatic springs (Fig. 1m) are the best and most effective packing for distillers. They constitute a professional filling in a rectification column, and perform catalytic functions. They clean distilled vapors from harmful and undesirable sulfur and hydrogen sulfide compounds, effectively dissipate heat, and at the same time provide airflow for the medium. The springs are produced as specially twisted wire of various sizes. In this paper, springs with a diameter of 4–5 mm and a length of 5–6 mm were used.

In this research, acorns were also used. However, they were made on the basis of the rapid prototyping system, which is colloquially called 3D printing (Fig. 1n) with the use of FDM (fused deposition modeling) technology. This technology consists of the gradual overlapping of layers of molten polymeric material. This method of printing ensures high resistance to mechanical damage and temperature changes, and therefore acorns made of acrylonitrile-butadiene-styrene (ABS) copolymer are more durable than natural ones. They all have the same dimensions, and their height is 2 cm.

Fig. 1. Used packings: (a) LECA, (b) garden pumice of 10–20 mm, (c) Piedmont ceramic tile from Roben Company, (d) clinker brick, (e) wood chips, (f) black alder cones, (g) larch cones, (h) pine cones, (i) walnuts, (j) coconut fiber, (k) shells, (l) bottle caps, (m) prismatic springs, and (n) ABS acorns.

2.3. Description of the measuring stand for determining the pressure drop on the packing

The research and experimental stand on which all the types of packings were tested consisted of the following elements: a column-tank for liquid, a compressor, a sprinkler, rotameters, and control valves. A photo of the measuring stand is shown in Fig. 2. The column, with an internal diameter D_w = 0.12 m and a total height H = 2 m in the working part, was equipped with elements that are responsible for developing the interfacial contact area, that is, a loosely piled packing of a certain height. Air was supplied to the installation through the control valves and the rotameter using a METABO MEGA 350-100D compressor, and it flowed to the bottom part of the column. The liquid was led to the top of the column, where it was evenly distributed by the sprinkler. The Cellfast multipurpose sprinkler Variant 50–750 was used. A 180° adjustable sprinkler head enabled for its precise positioning in the axis of the column, and also for the selection of the appropriate type of stream – from a strong single stream, through a delicate mist, to a strong shower and a delicate shower. It allowed the spraying of the liquid to be selected with regards to the demands and process requirements. Gas and liquid flowed through the column that was counter-currently packed. The valves placed in front of the Kytola HV 4 rotameters enabled the gas and liquid flow rates to be regulated. In turn, the U-tube pressure gauge was used to determine the drop of pressure on the packing.

2.4. Methodology of testing the pressure drop and parameters of the packing

Pressure drop measurements were carried out for single-phase and two-phase flows. In the case of the single-phase flow, the pressure drop was determined for all the packings within the range of the gas flow rate from 0.1 to 0.6 m^3/min. In the case of the two-phase flow, the pressure drop was determined for all the packings within the range of the liquid flow rate from 0.2 to 1.0 m^3/h. The directly measured values were: the temperature of the media, the drop of pressure on the packing ΔP_s, and the volumetric flow rate of the gas Q_g and liquid Q_l.

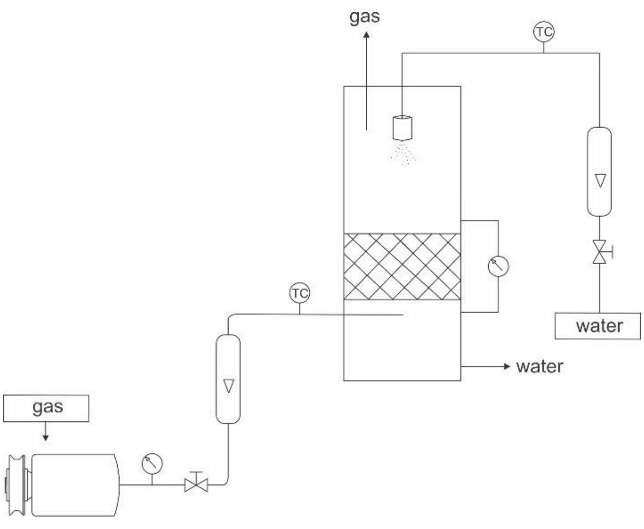

Fig. 2. Scheme of the experimental installation.

At the outset, the porosity ε and the bulk density ρ_s had to be determined for each of the tested packings. The porosity was determined from the following formula:

$$\varepsilon = \frac{V_s}{V_z} = \frac{V_z - V_e}{V_z} = \frac{f_e}{f_0} \tag{1}$$

where V_z is the total volume of the packing, V_s is the free volume between the elements of the packing, and V_e is the volume of the elements/material. f_0 is the column's cross-sectional area, and f_e is the cross-sectional area not occupied by a solid phase or elements. Bulk density was determined by measuring the packing with a known volume, and then weighing it. Table 1 summarizes the calculated values [d_e is calculated from Eq. (8)].

The hydraulics of both the gas and liquid flow through the packing layer are directly influenced by two values that are related to the shape and dimensions of the elements that constitute this layer. These are:

- free volume (the so-called porosity) of the packing ε, which is defined as the ratio between the volume of voids in a layer to the volume of the entire layer,
- unit area of packing a, which is defined as the size of the developed area that is represented by 1 m^3 of a given packing.

Parameters ε and a are related to one more quantity that characterizes the dimensions of the packing. Due to the complex and diverse shape of these elements, it is necessary to define a substitute parameter that allows them to be compared in terms of size. For this purpose, the concept of an equivalent diameter was introduced, which is usually defined as:

$$d_e = \frac{4\varepsilon}{a} \tag{2}$$

In literature, in addition to the definition of the equivalent diameter according to Eq. (2), other definitions of this quantity can be found. This particularly applies to the equations describing the course of mass exchange processes that are carried out in packed columns. The authors of these equations sometimes assume the following expressions as the equivalent diameter of the elements of the packing:

$$d_e = \frac{\varepsilon}{a},\ d_e = \frac{1}{a},\ d_e = \sqrt{\frac{F_e}{\pi}},\ d_e = \sqrt[3]{\frac{6V_e}{\pi}} \tag{3}$$

where: F_e is the area of one packing element, and V_e is the volume of one packing element.

In practice, when using the equivalent diameter, the way of defining it should always be taken into consideration. Such a definition does not always accurately describe the packing, as, in the case of coconut fiber for example, it is difficult to determine the exact area, volume and number of fibers. Based on the air flow rate and its density, the mass flow rate M_g was determined, while the porosity of

Table 1
Comparison of the results of the porosity and bulk density for the tested packings

Type of packing	Designation	ε (–)	ρ_s (g/cm³)	F_e (cm²)	V_e (cm³)	d_e (cm)
LECA	KER	0.445	0.324	5.3	1.2	1.36
Pumice 4–8 mm	PUM-S	0.460	0.599	1.5	0.35	1.36
Pumice 10–20 mm	PUM-B	0.535	0.356	18.9	2.8	0.89
Roof tile	TC	0.560	0.934	26.6	4	0.90
Brick	BC	0.540	0.978	40.2	6.7	1.00
Wooden chips	WCH	0.640	0.214	4.7	0.27	0.34
Black alder cones	BACO	0.770	0.136	6	0.6	0.60
Larch cones	LCO	0.800	0.129	11.5	5.2	5.20
Pine cones	PCO	0.890	0.088	8	8	6.00
Walnuts	ITN	0.500	0.403	22	11.6	3.16
Coconut fiber	CFI	0.94	0.029	3.4	0.0085	0.015
Small shells	SH-S	0.670	0.723	11	1.2	0.65
Large shells	SH-B	0.680	0.695	23	2.4	0.63
Small bottle caps	SC-S	0.780	0.153	37	2.2	0.36
Large bottle caps	SC-B	0.820	0.116	55	3.12	0.34
Copper springs	CS	0.750	1.337	1	0.0025	0.015
Acorns	AC	0.360	0.235	9	3	2.00

the packing and the diameter D of the column were used to calculate coefficient f_e according to the following formula:

$$f_e = \varepsilon \cdot f_0 = \varepsilon \cdot \frac{\pi D^2}{4} \quad (4)$$

Both parameters were used to calculate the equivalent mass velocity g_g, which is expressed by equation:

$$g_g = \frac{M_g}{f_e} \quad (5)$$

3. Results and discussion

3.1. Single-phase flow analysis

The lines of the dependence of the pressure drop on the packing, which correspond with the gas flow through the dry (not drenched) packing, are straight. The straightness of this relationship in the adopted coordinate system results from the fact that in this case the stationary packing layer is only a permanent local obstacle for the flow of gas (such as a valve or an elbow).

An exemplary dependence of the pressure drop per meter of the packing is shown in Fig. 3. Fig. 3a compares the pressure drops that occur in the packing made of LECA (KER) and garden pumice (with different fractions) during the gas flow through the column. Based on the data analysis, it can be concluded that the pumice stone with a fraction of 10–20 mm (PUM-B) achieves the lowest pressure drops. In turn, the highest pressure drops were found in the pumice with a grain size of 4–8 mm (PUM-S). It is obvious that the pressure drops increase the more fragmented the material is. It was also observed that smaller shells had slightly greater pressure drops than larger shells. A similar dependence was also seen in the case of the nuts – those with a diameter of 28 mm had greater pressure drops than those with a larger diameter.

The main cause of the pressure drop during the gas flow through the packing elements is the change in the velocity of the flowing gas and the expansion that is associated therewith. Jaroszyński et al. [24] and Maćkowiak [25] most often adopt a channel model to derive equations that describe the pressure drop at a single-phase flow through a stationary packing layer. This model treats the packing layer as a set of equal and parallel channels, while at the same time assuming an isothermal gas flow. The Darcy–Weisbach equation can then be used to describe the pressure drop on dry packing, which after appropriate modification takes the form [25]:

$$\frac{\Delta P}{H} = \psi \frac{1-\varepsilon}{\varepsilon^2} \frac{1}{K} \frac{v_{og}^2 \rho_g}{d_e} \quad (6)$$

where ΔP – pressure drop, H – packing height, $\psi = 0,75\lambda$ – flow resistance coefficient that is dependent on the Reynolds number, K – coefficient that takes into account the influence of the column's wall, v_{og} – velocity of the gas flow related to the total cross-section of the column, ρ_g – gas density.

The K factor is defined by the following relationship:

$$K = \frac{1}{1 + \frac{2}{3} \frac{\varepsilon}{1-\varepsilon} \frac{d_e}{D}} \quad (7)$$

The equivalent diameter of the packing element is calculated from the following equation:

$$d_e = 6 \frac{V_e}{F_e} \quad (8)$$

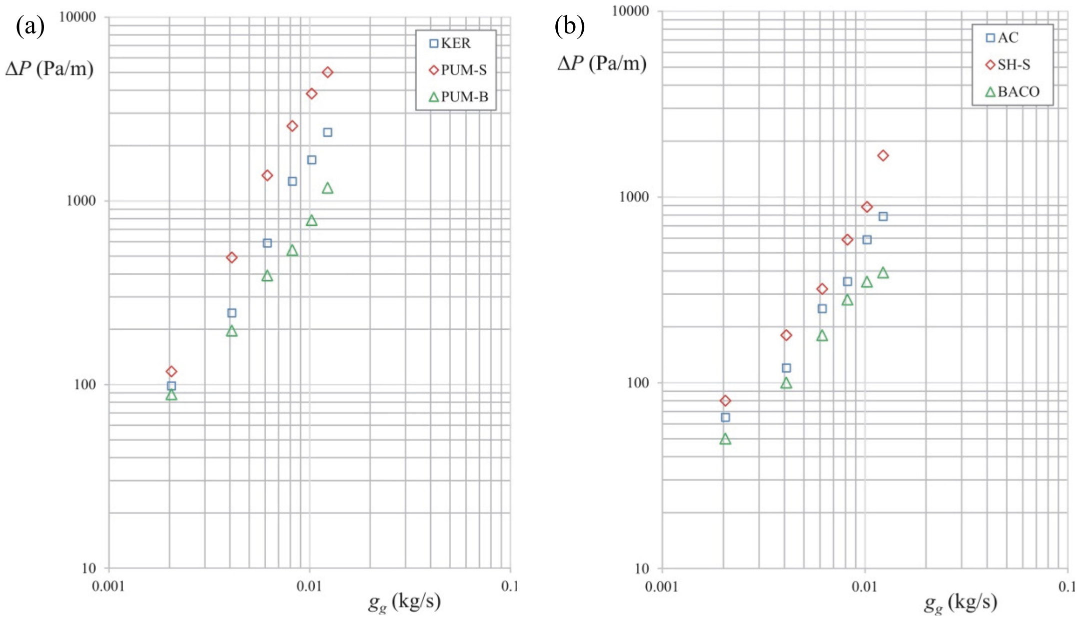

Fig. 3. Dependence between the pressure drop on the selected packings and the equivalent mass velocity g_g: (a) selected ceramic materials and (b) selected materials of various shapes.

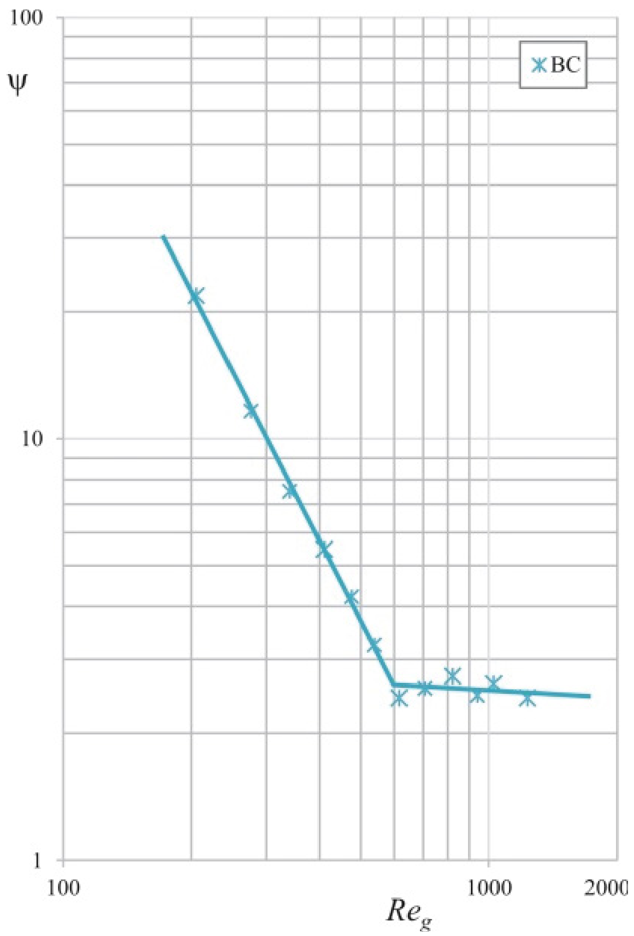

Fig. 4. Dependence between the flow resistance coefficient and the Reynolds number for a loose-packed BC packing.

The Reynolds number is defined as follows:

$$\mathrm{Re}_g = K\frac{1}{1-\varepsilon}\frac{v_{og} d_e \rho_g}{\eta_g} \tag{9}$$

where η_g – dynamic coefficient of gas viscosity.

The relationship between the flow resistance coefficient ψ and the Reynolds number is as follows:

$$\psi = C\,\mathrm{Re}_g^B \tag{10}$$

where C, B – constants that depend on Re_g and the type and size of the packing element.

The plot area for Maćkowiak's model [25] should be divided into two parts that are separated by a characteristic point that marks the change in the nature of the gas flow (Fig. 4). Note that this function is a power function described by Eq. (10).

In the case of the brick (BC) packing with the average dimensions of the elements of 2.1 cm × 3.3 cm × 1.9 cm (the surface of the element corresponds to a sphere with a diameter of 3.6 cm, and its equivalent diameter calculated from Eq. (8) is equal to 1 cm), both the laminar range (from Re_g to 600) and the turbulent range (Re_g > 600) can be noticed. In turn, in the case of, for example, the PUM-S packing, it is nearly just the turbulent range that can be observed (Fig. 5). The analysis of the selected measurement points presented in Fig. 5 showed that it was not only different values of the flow resistance coefficient that were obtained for each type of packing, but also different values of the Reynolds number. For example, at the same gas flow rates, the copper springs (CS) packing worked in the Re number range from 6 to 40, the coconut fiber packing in the Re range from 25 to 170, and the pine cones (PCO) packing in the

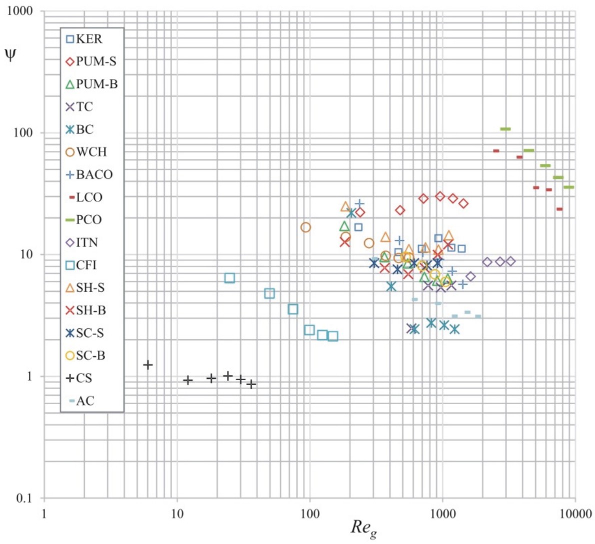

Fig. 5. Dependence between the flow resistance coefficient and the Reynolds number for the tested packings (selected experimental points).

Re range from 3,000 to 9,000. Most of the packings worked in the Re number value range from 200 to 2,000. The highest values of the flow resistance coefficient were observed for the PCO and larch cones (LCO) packings (values of 100), with the lowest being observed for the CS ones (values of 1). Laminar movement, if it occurs in the case of these packings, takes place within the range of much smaller Reynolds numbers than is the case with the BC packing. Therefore, the structure of the BC packing favors the laminar flow more than the PUM-S packing. The LCO and PCO packings are characterized by high flow resistance coefficients, and the CS packing by very low flow resistance coefficients. Table 2 summarizes the values of the flow resistance coefficients at the maximum value of the set flow rate.

Table 2
Summary of flow resistance coefficients for the tested packings

Packing	ψ (–)
KER	11.2
PUM-S	26.1
PUM-B	6.1
TC	5.4
BC	2.4
WCH	9.4
BACO	5.6
LCO	23.0
PCO	35.7
ITN	8.6
CFI	2.1
SH-S	8.2
SH-B	10.7
SC-S	8.4
SC-B	5.9
CS	0.85
AC	3.1

3.2. Two-phase flow analysis

In the adopted model [25], the relationship between the pressure drop on the sprayed packing ΔP_m and the pressure drop on the dry packing ΔP is presented in the form of the following formula:

$$\frac{\Delta P_m}{\Delta P} = f\left(K_p\right) \tag{11}$$

where:

$$K_p = \mathrm{Fr}_l \mathrm{Re}_l^{-0.8}\left(1 + 5 \cdot 10^{-5} \mathrm{Re}_g\right) \tag{12}$$

$$\mathrm{Fr}_l = \frac{v_{\mathrm{ol}}^2 \left(1-\varepsilon\right)}{g d_e K} \tag{13}$$

$$\mathrm{Re}_{l,g} = \frac{v_{\mathrm{ol,og}} d_e \rho_{l,g}}{\eta_{l,g}\left(1-\varepsilon\right)} K \tag{14}$$

Relationship (11) is described by equation:

$$\frac{\Delta P_m}{\Delta P} = A\exp\left(BK_p\right) \tag{15}$$

The graphic illustration of which for the selected packings is shown in Figs. 6 and 7.

The work areas of a given type of packing were marked in Figs. 6 and 7 with ellipses. The curves, which are based on Eq. (15), are not straight linear dependences.

On these curves, characteristic points (Fig. 8) that make up the overload line and the choke line can be distinguished. Below the overload line, the amount of liquid suspended on the packing increases as the spraying density increases, but is independent of the gas velocity. A further increase of the gas velocity hinders the flow of the liquid, and its retention on the packing elements is strongly increased. This consequently leads to the reaching of a certain limit point – the so-called choking of the apparatus. Note that this function is an exponential function described by Eq. (15). This phenomenon is widely described in literature [26–28]. The inhibitory effect of the gas is then so great that the entire apparatus is filled with liquid, with its operation resembling that of a scrubber column, which additionally contains a packing layer that does not fulfill its role. This condition limits the ability of the apparatus to function, and the possibility of its occurrence must be the subject of verifying calculations in the course of designing such apparatus. The working point of a packed column is usually slightly above the overload point, but always below the choke point. The values of constant A and exponent B from Eq. (15) for the tested packings are given in Table 3. These values were determined with the use of the least squares method using the Levenberg–Marquardt estimation method. The most important is the value of A,

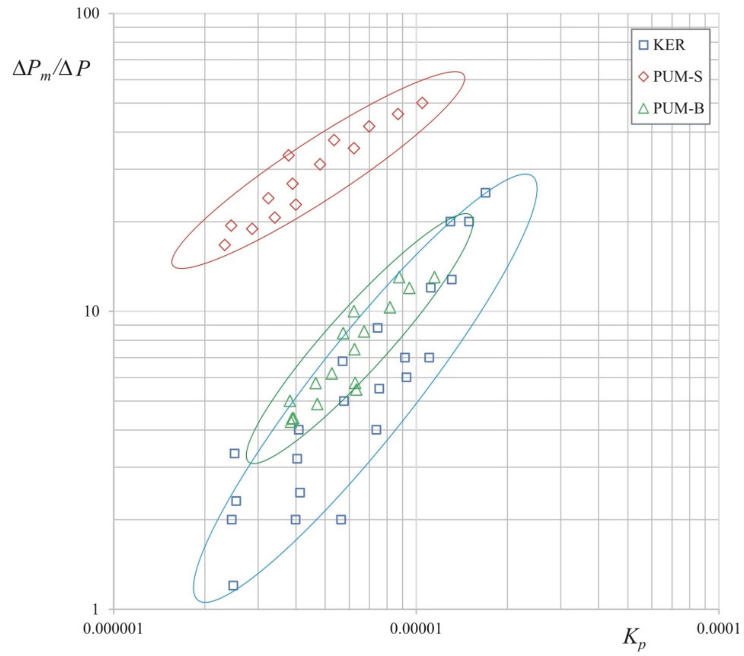

Fig. 6. Dependence between the ratio of the pressure drop on the sprayed packing to the pressure drop on the dry packing, and the K_p coefficient for the selected packings.

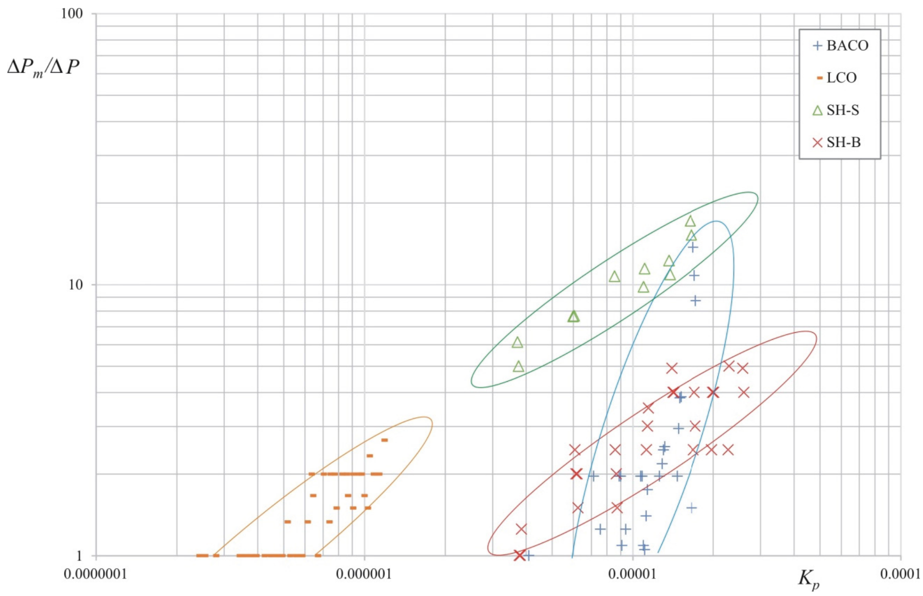

Fig. 7. Dependence between the ratio of the pressure drop on the sprayed packing to the pressure drop on the dry packing, and the K_p coefficient for the selected packings.

which is due to the fact that it determines the increase value of the $\Delta P_m/\Delta P$ ratio. It was shown that the largest increase in $\Delta P_m/\Delta P$ was observed for the PUM-S (around 20 at K_p = 0.000001), while for most of the tested packings, the $\Delta P_m/\Delta P$ ratio reached values of the order of $1 < \Delta P_m/\Delta P < 5$.

Eq. (15) can describe line $\frac{\Delta P_m}{\Delta P} = f\left(K_p\right)$ with an average accuracy of ±35%. This is a satisfactory and even good result [29] due to the fact that multiphase flow, during which many processes and interactions occur that are difficult to predict and describe, was considered. Due to large discrepancies in the results obtained for the coconut fiber and copper springs (which is the result of, among others, a difficult flow of fluids in the countercurrent), it was decided not to provide values of constants A and B for these packings. Fig. 9 shows an exemplary comparison of the experimental data with the data obtained from Eq. (15) for the small shells packing.

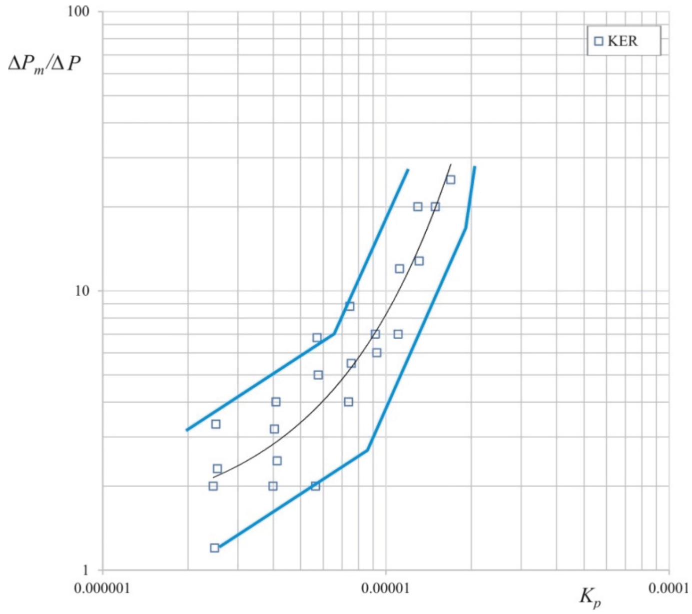

Fig. 8. Dependence between the ratio of the pressure drop on the sprayed packing to the pressure drop on the dry packing, and the K_p coefficient for packing KER.

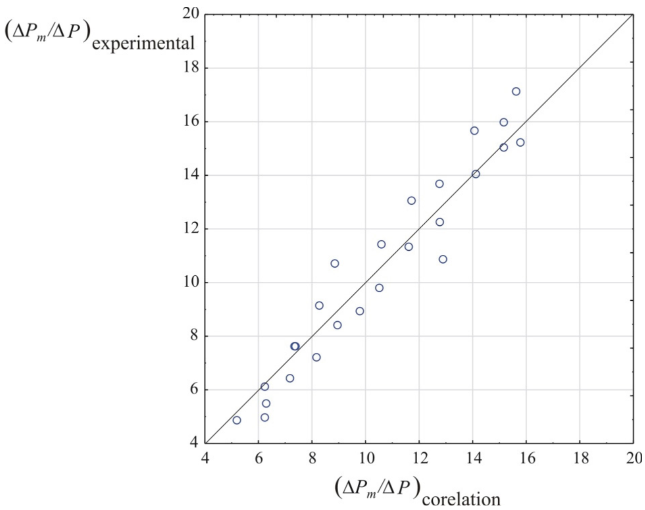

Fig. 9. Comparison of the experimental data with the data obtained from correlative Eq. (15) for the SH-S packing.

4. Conclusions

The use of various types of packings, both of natural and waste origin, enabled an experimental stand to be created for testing the drops of pressure in a column with regards to the flow velocity of the used gas and liquid. The performed calculations allowed the influence of geometry, weight and origin on the fluidization effect to be determined. Due to this, it is possible to define which of the used elements can be used as packing.

Based on the conducted experiment, it can be concluded that:

- Flow resistance increases with an increase in gas and liquid velocity. This phenomenon is visible in the case of a single-phase and two-phase flow.
- In the case of the two-phase flow, the pressure drop was greater than in the case of the single-phase flow. Under critical flow conditions, the moment of the column choking was noticeable, and depended on the type of the used packing.
- In the single-phase flow, the highest pressure drops were obtained with the use of pumice stone of 4–8 mm, and the lowest pressure drops were obtained using larch cones. However, with the simultaneous introduction of liquid and gas into the circulation, the first to be flooded was the packing composed of pneumatic springs, followed by the packing with two types of pumice and small shells.
- The lowest pressure drops, and thus a lack of fluidization, was noted when using larch cones, which in turn became the best type of packing. The use of alder cones and acorns was also very favorable. In turn, in the case of low speeds, chipped brick and nuts with a diameter of 28 mm worked well.
- The highest values of the flow resistance coefficient for one phase flow were observed for the PCO and LCO packings, and the lowest for the CS packing. The lowest value of Ψ was observed for the copper springs (CS) Ψ = 0.85 and the highest value Ψ = 35.7 was observed for pine cones (PCO). All the values of Ψ are presented in Table 2.
- The equation of the following form $\Psi = C\text{Re}_g^B$ for the one phase flow was analyzed.
- For two phase flow, the values of A and B in the equation: $\frac{\Delta P_m}{\Delta P} = A\exp\left(BK_p\right)$ were determined, and the largest increase in $\Delta P_m/\Delta P$ was observed for PUM-S (around 20 at $K_p = 0.000001$).
- The adopted model accurately describes the pressure drop on the sprayed packing for each of the tested packings.

Table 3
The values of constants *A* and *B* in Eq. (11) together with the coefficient of adjustment *R*

Designation	*A* (–)	*B* (–)	*R*
KER	1.7 ± 0.31	161,081 ± 12,764	0.951
PUM-S	20.9 ± 3.8	88,565 ± 22,780	0.901
PUM-B	3.0 ± 0.7	137,108 ± 28,260	0.871
TC	3.6 ± 0.9	273,796 ± 84,526	0.881
BC	3.5 ± 1.48	43,300 ± 14,546	0.587
WCH	18.3 ± 5.4	94,353 ± 34,828	0.539
BACO	0.3 ± 0.07	170,083 ± 51,523	0.823
LCO	0.7 ± 0.1	827,914 ± 269,220	0.724
PCO	0.7 ± 0.1	753,245 ± 257,980	0.586
ITN	1.2 ± 0.5	125,504 ± 59,753	0.802
SH-S	4.75 ± 0.54	72,347 ± 8,558	0.949
SH-B	1.59 ± 0.31	39,129 ± 13,600	0.675
SC-S	3.4 ± 0.45	24,380 ± 10,440	0.600
SC-B	1.18 ± 0.33	23,096 ± 11,200	0.597
AC	2.9 ± 0.86	203,747 ± 65,640	0.660

These tests constitute the basis for further studies of packings of various origins in order to determine the influence of variable geometrical dimensions, as well as the physicochemical parameters of liquid and gas on the value of the pressure drop and the moment of flooding the packing.

Acknowledgements

The work was funded with a grant from the Polish Ministry of Education and Science.

References

[1] Y. Son, G. Kim, S. Lee, H. Kim, K. Min, K.S. Lee, Experimental investigation of liquid distribution in a packed column with structured packing under permanent tilt and roll motions using electrical resistance tomography, Chem. Eng. Sci., 166 (2017) 168–180.

[2] Y. Son, S. Lee, S. Han, D. Yang, K. Min, K.S. Lee, Liquid distribution model based on a volume cell for a column with structured packing under permanent tilt and roll motions, Chem. Eng. Sci., 182 (2018) 1–16.

[3] Z. Xiaobin, Y. Lei, Q. Limin, Z. Xuejun, Three-dimensional computational fluid dynamics modeling of two-phase flow in a structured packing column, Chin. J. Chem. Eng., 21 (2013) 959–966.

[4] X. Di, W. Wang, S. Chen, Y. Huang, Effect of tilt on mass transfer and hydrodynamic performance in a packing column, Chem. Eng. Process. Process Intensif., 123 (2018) 89–99.

[5] P. Sánchez1, E.J.P. Sánchez, R.S. Silva, Design of a packed-bed absorption kolumn considering four packing types and applying Matlab, Nexo: Revista Cientifica, 29 (2016) 83–104.

[6] A.N. Pavlenko, N.I. Pecherkina, V.E. Zhukov, A.D. Nazarov, G. Meski, P. Houghton, Separation efficiency of mixtures by distillation using structured noncircular packings, Chem. Eng. Process. Process Intensif., 133 (2018) 211–220.

[7] H. Li, S. Li, Optimization of continuous solid-state distillation process for cost-effective bioethanol production, Energies, 13 (2020) 854, doi: 10.3390/en13040854.

[8] X. Zhao, K.H. Smith, M.A. Simioni, W. Tao, S.E. Kentishb, W. Fei, G.W. Stevens, Comparison of several packings for CO_2 chemical absorption in a packed columns, Int. J. Greenhouse Gas Control, 5 (2011) 1163–1169.

[9] B. Xu, H. Gao, X. Luo, H. Liao, Z. Liang, Mass transfer performance of CO_2 absorption into aqueous DEEA in packed columns, Int. J. Greenhouse Gas Control, 51 (2016) 11–17.

[10] C. Wendt, R. Ives, A.L. Hoyt, K.E. Conrad, S. Longstaff, R.W. Kuennen, J.B. Rose, Microbial removals by a novel biofilter water treatment system, Am. J. Trop. Med. Hyg., 92 (2015) 765–772.

[11] T. Fletcher, Y. Zinger, A. Deletic, K. Bratieres, Treatment Efficiency of Biofilters; Results of a Large-Scale Column Study, in: Rainwater and Urban Design 2007, Barton, A.C.T.: Engineers Australia, 2007, pp. 266–273. Available at: https://search.informit.org/doi/10.3316/informit.889322693950718

[12] F. Canul Bacab, E. España Gamboa, J.E. Ruiz Espinoza, R.M. Leal-Bautista, R. Tapia Tussell, J. Domínguez Maldonado, B. Canto Canché, L. Alzate-Gaviria, Two phase anaerobic digestion system of municipal solid waste by utilizing microaeration and granular activated carbon, Energies, 13 (2020) 933, doi: 10.3390/en13040933.

[13] K. Kozłowska, B. Bańka, Neutralization of odors generated during composting of biodegradable fraction of municipal and industrial waste by biofiltration, Eng. Environ. Prot., 17 (2014) 631–645.

[14] J. Warych, Purification of Gases: Processes and Apparatus, WNT, Warszaw, Poland, 1998.

[15] A. Muszyński, A. Tabernacka, M. Załęska-Radziwiłł, How to reduce the emission of microorganisms from a biofilter used to treat waste gas from a food industry plant, Atmosphere, 12 (2021) 673, doi: 10.3390/atmos12060673.

[16] M. Wierzbińska, Biofiltracja przemysłowych gazów odlotowych przy użyciu naturalnych złóż włóknistych, II Kongres Inżynierii Środowiska, Lublin, Poland, 1 (2009) 263–271.

[17] J. Kwaśny, W. Balcerzak, Characteristics of selected indirect methods of reducing the emission of odors, Arch. Waste Manage. Environ. Prot., 16 (2014) 125–134.

[18] U.F. Carreño Sayago, Design, scaling, and development of biofilters with e crassipes for treatment of water contaminated with Cr(VI), Water, 13 (2021) 1317, doi: 10.3390/w13091317.

[19] M.A. Deshusses, D. Gabriel, Biotrickling Filter Technology, in: Biotechnology for Odor and Air Pollution Control, Springer-Verlag, Berlin, Heidelberg, 2005, pp. 147–166.

[20] http://www.wypelnieniastrukturalne.pl, 2020 (accessed 13 March 2020).

[21] https://www.tandfonline.com/doi/pdf/10.3155/1047–3289.59.5.520, 2020 (accessed 24 February 2020).

[22] R. Premkumar, S. Devi, N. Krishnamohan, A. Balaji, Wood chip based filter media for removal of pollutants from waste air: review, Int. J. ChemTech Res., 5 (2013) 2830–2836.

[23] A.A. Nazari-Moghaddam, G.D. Najafpor, A.A. Ghoeyshi, M. Mohammadi, S. Zein, Removal of methylene blue from aqueous phase by pretreated walnut shell in a packed column, Iran. J. Energy Environ., 1 (2010) 137–143.

[24] M. Jaroszyński, A. Kołodziej, I. Bylica, W. Smolec, Hydrodynamics of columns with structured reactive packing, Chem. Proc. Eng., 21 (2000) 691–705.

[25] J. Maćkowiak, Fluid Dynamics of Packed Columns, Principles of the Fluid Dynamic Design of Columns for Gas/Liquid and Liquid/Liquid Systems, Springer Verlag, Berlin-Heisenberg, 2010.

[26] M. Asadollahzadeh, A. Haghighi Asl, J. Safdari, M. Torab-Mostaedi, Flooding characteristics in pulsed packed extraction columns, Braz. J. Chem. Eng., 28 (2011) 625–638.

[27] T. Barletta, J. Nigg, S. Ruoss, J. Mayfield, W. Landry, Diagnose Flooding Columns Efficiently, Hydrocarbon Proc., 2001, pp. 71–75.

[28] G. Senger, G. Wozny, Impact of foam to column operation, Tech. Trans., 5 (2012) 209–222.

[29] T. Komorowicz, K. Kupiec, A. Głuszek, M. Rodak, Comparative analysis of packed column hydraulics, Chem. Eng. Equip., 53 (2014) 153–154.