ESTUDO EXPERIMENTAL DE RESISTÊNCIA HIDRÁULICA DE FLUXO TURBULENTO EM UMA CAMADA COMPACTADA**EXPERIMENTAL STUDY OF THE HYDRAULIC RESISTANCE OF TURBULENT FLOW IN THE PACKED BED****ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ ГИДРАВЛИЧЕСКОГО СОПРОТИВЛЕНИЯ ТУРБУЛЕНТНОГО ПОТОКА В УПЛОТНЕННОМ СЛОЕ**

KULYMBAYEVA, Marzhan Sh.¹; ORUMBAYEV, Rakhimzhan K.^{2*}; SEIDALIYEVA, Aiganyam B.²; OTYNCHIYEVA, Marzhan T.²; MUNTS, Vladimir A.³;

¹ Kazakh-German University; Faculty of Engineering and Information Technology; 111 Pushkin Str., zip code 050010, Almaty – Republic of Kazakhstan

² Almaty University of Power Engineering and Telecommunications named after Gumarbek Daukeyev; Institute of Heat Power Engineering and Control Systems; Department of Thermal Power Plants; 126/1 Baytursynuli Str., zip code 050013, Almaty – Republic of Kazakhstan

³ Ural Federal University named after the First President of Russia B.N. Yeltsin; Ural Power Engineering Institute; Department of Thermal Energy and Engineering; 19 Mira Str., zip code 620002, Ekaterinburg – Russian Federation

* Correspondence author
e-mail: r.orumbayev@aukes.kz

Received 01 October 2020; received in revised form 28 October 2020; accepted 15 November 2020

RESUMO

Vários dispositivos com inserções porosas e peneiras são amplamente usados em processos de produção modernos. Esses dispositivos são usados para desativar as emissões industriais e substâncias tóxicas e nocivas na indústria de energia térmica e automotiva, bem como para eliminar gases de exaustão na metalurgia de metais não ferrosos. A eficiência do funcionamento de tais dispositivos depende em grande parte do movimento bem organizado de um meio gasoso ou líquido, que tem grande influência nos processos de transferência de calor e massa dentro do reator e determina o seu grau de eficiência. Este artigo é dedicado à resistência hidráulica do movimento do fluido incompressível (ar) no tubo redondo com inserções porosas feitas de pacotes de cartuchos com pequenas células. Novos resultados e dados foram obtidos sobre a resistência hidráulica das inserções porosas representadas por uma malha fina, alinhamento do perfil da velocidade média na frente da malha e alteração do componente longitudinal da intensidade de turbulência da estrutura de fluxo turbulento. Para o cálculo da pressão estática, foram utilizados orifícios de drenagem com diâmetro de 5×10^{-4} m, localizados em diferentes partes da área de trabalho do tubo, dentro das inserções porosas entre as malhas e após as inserções na área de saída de estabilização do bloco. A medição das características médias de velocidade e impulso do fluxo de ar foi realizada por meio do anemômetro de perda de calor, regulado em uma temperatura constante. Foi demonstrado experimentalmente que existe um equilíbrio local entre os processos de geração e dissipação de energia de turbulência dentro das inserções porosas representadas por uma malha fina. Como resultado, foi estabelecido que existe um equilíbrio local entre os processos de geração e dissipação de energia de turbulência dentro de insertos porosos feitos de malhas finas. Verificou-se que a intensidade da turbulência permanece no mesmo nível e depende das características geométricas das grades e da vazão de ar.

Palavras-chave: *cartuchos, energia de turbulência, pressão, fluido incompressível.*

ABSTRACT

Modern production processes widely involve various apparatus with porous inserts and screens. Similar devices are used to decontaminate industrial emissions or the neutralization of toxic and harmful substances in heat energetics and automotive industries and the utilization of exhaust gases in the non-ferrous metal industry. The operational efficiency of such devices vastly depends on the correctly organized movement of gas or liquid medium, which has a significant influence on heat and mass exchange processes within the reactor and defines

Its efficiency rate. This article is about the hydraulic resistance movement of incompressible liquid (air) in a circular tube with porous inserts made from cartridge packs with fine meshes. There were obtained new results and data on hydraulic resistance of porous inserts represented by fine mesh, leveling out the profile of averaged speed before the mesh, and change of longitudinal constituent of the turbulence intensity turbulent flow structure. To calculate the static pressure, some 5×10^{-4} m diameter drainage holes were used, located in different parts of a tube operating area, within the porous inserts between meshes and after inserts at the unit's stabilizing output region. Measurement of an average speed and impulse characteristics of airflow was performed with a heat loss anemometer set to the constant temperature value. It was shown by the experiment that there is a local balance existing between turbulence energy generation and dissipation processes within the porous inserts represented by fine mesh. As a result, it was found that there is a local balance between the processes of generation and turbulence energy dissipation inside porous inserts made of fine meshes. It was determined that the intensity of turbulence remains at the same level and depends on the geometric characteristics of the meshes and airflow rate

Keywords: *cartridge packs, turbulence energy, pressure, incompressible liquid.*

АННОТАЦИЯ

В современных производственных процессах широко используются различные аппараты с пористыми вставками и ситами. Подобные устройства используются для обезвреживания промышленных выбросов или для нейтрализации токсичных и вредных веществ в теплоэнергетике и автомобильной промышленности, а также для утилизации выхлопных газов в цветной металлургии. Эффективность работы таких устройств в значительной степени зависит от правильно организованного движения газовой или жидкой среды, что оказывает большое влияние на процессы тепло- и массообмена внутри реактора и определяет степень его эффективности. Эта статья посвящена гидравлическому сопротивлению движения несжимаемой жидкости (воздуха) в круглой трубе с пористыми вставками, выполненными из пачек картриджей с мелкими ячейками. Получены новые результаты и данные по гидравлическому сопротивлению пористых вставок, представленных мелкой сеткой, выравнивание профиля усредненной скорости перед сеткой и изменение продольной составляющей интенсивности турбулентности структуры турбулентного потока. Для расчета статического давления использовались дренажные отверстия диаметром 5×10^{-4} м, расположенные в разных частях рабочей области трубки, внутри пористых вставок между сетками и после вставок в стабилизирующей выходной области блока. Измерение средней скорости и импульсных характеристик воздушного потока проводилось с помощью анемометра потери тепла, установленного на постоянное значение температуры. Экспериментом было показано, что существует локальный баланс между процессами генерации энергии турбулентности и диссипации внутри пористых вставок, представленных тонкой сеткой. В результате установлено, что между процессами генерации и рассеивания энергии турбулентности внутри пористых вставок из мелких сеток существует локальный баланс. Установлено, что интенсивность турбулентности остается на одном уровне и зависит от геометрических характеристик сеток и скорости воздушного потока.

Ключевые слова: *картриджи, энергия турбулентности, давление, несжимаемая жидкость.*

1. INTRODUCTION

Modern production processes widely involve various apparatus with porous inserts and screens. Chemical oil and chemical industry, heat energetics, and other related industries have experienced widespread reactors with immovable grain or a mesh layer of catalyst. Similar devices are used to decontaminate industrial emissions or the neutralization of toxic and harmful substances in heat energetics and automotive industries and the utilization of exhaust gases in the non-ferrous metal industry. As a rule, such units are represented by two side-by-side channels connected via a common passable wall. The most vivid example of such a unit is a

displacement reactor, which consists of a direct flow channel with a porous insert. The working principle of such units may be described as follows: oncoming movement of liquid with certain speed onto the passable insert. The liquid continues its movement further down the free portion of a channel being filtered through this insert. Simultaneously, the flow that moves through the porous structure is slowing down, and therefore part of the liquid goes from the central area of the channel to its sides (peripheral area), where the flow speed is lower. Afterward, coming through the porous insert, and depending on the characteristics of the porous insert itself, the liquid continues to distribute in a radial direction. Having passed through the porous

insert, the flow then starting to increase speed again due to the direct flow portion of a channel. However, one may observe significant inconsistencies in speed values, causing further degradation down the flow.

The operational efficiency of such devices vastly depends on the correctly organized movement of gas or liquid medium, which has a great influence on heat and mass exchange processes within the reactor and defines its efficiency rate. First of all, it requires the creation of a more stable and balanced distribution of flow within the active layer of devices with high unit capacity, because along with the growth of geometric sizes of the reactor, all the relative values between separate elements of the device will be changed as well. The overall volume of the device, the volume of the reactive area, the section area of the holes through which the reaction mixture is supplied, and the receiving surface of the catalytic layer. All this leads to the change of the aerodynamic scheme of the medium movement and causes a high risk of spatial nonuniformity, which decreases the efficiency of the technological process. Research of efficiency matters referred to studies on features of liquid flow can be divided into several sections. The flow of the liquid within the direct flow portion of the unit was studied well already because they can be accurately described using Navier-Stokes equations for laminar flow (Sergeev *et al.*, 1974; Ershin *et al.*, 1990; Vlasov, 1991; Astanovskii and Astanovskii, 2005). Research of operating modes of turbulent flow units currently is of a much bigger interest.

So, it can be said that the task of optimal control and operational efficiency increase for units with porous layers will be solved if one would know for sure a consistent pattern of liquid and gas flows within the mentioned units. Generally, basic mathematic models for the operation of such units are represented in one measuring dimension (Vaisman and Goldshtik, 1978; Goldshtik, 1985; Esakov and Kotelkin, 1986; Evtushenko and Kotelkin, 1991). However, such an approach does not allow to perform complete research of different features of liquid or gas flows of the real-life unit (McSherry *et al.*, 2016; Wałowski and Filipczak, 2017; Maciel and Camara, 2019). This influence may be researched by the creation of a two-dimension flow model. However, solving the task in such a manner, the most difficult problem would be the accurate definition of the relation between the units operation mode and Reynolds number as the main hydrodynamic parameter (Zhizhkin *et*

al., 2018). Thus, the priority task is to research flow modes of actual liquid within units with porous structures of a certain shape (Vortmeyer and Schuster, 1983; Genbach *et al.*, 2016; Zhizhkin *et al.*, 2018). Simultaneously, one has to consider the location and structure of a porous environment as a whole factor without division into the research of the direct flow section and research of a porous layer itself. The research interest area goes beyond the study of the laminar movement of liquid based on solving accurate equations of Navier-Stokes and involves studying turbulent movement within units with the stationary porous layer. The last task in particular – research of turbulent movement – suggests, in the first place, a creation of a two-dimension measuring model based on a sufficient amount of research material concerning the flow within a channel equipped with passable porous walls or inserts.

The majority of studied research works on flow hydrodynamics after porous layer (Showkat Ali *et al.*, 2017; Wałowski and Filipczak, 2017; Bhattacharjee *et al.*, 2019; Maciel and Camara, 2019) mention macroscopic flow inconsistencies at the moment of porous layer exit – an increase of flow speed next to channel walls and decrease of flow speed in the middle. Interestingly enough, lots of research works were focused on studying the structure within the stationary porous layer itself. Simultaneously, it was believed that speed profiles beyond the porous layer are identical to flow distribution within that layer. However, several studies (Kirillov *et al.*, 1979; Volkov *et al.*, 1984) showed that in matching average flow speed profiles within the porous layer and beyond, local speed profiles would differ heavily. Research on tightly packed and dispersed sets of meshes showed equal result values of hydraulic resistance. It has brought the opportunity to establish an experiment within a direct flow channel with a porous insert and to measure flow characteristics inside the porous layer of the unit.

2. MATERIALS AND METHODS

The study of the hydraulic resistance of turbulent flow in the packed bed were carried out on an experimental installation (Figure 1). A profiled jet 1 named after Vitoshinskiy was installed in the water intake area (Yushko, 2015), which had nine stages of contraction connected with the main channel 2, a 0.05 m and on a 0.1mm distance from the jet itself there was also installed a shaped honeycomb 3. To measure the static pressure, some drainage holes of 5×10^{-4} m in diameter were used, which were located in

different sections of the operating area of the tube, inside the porous inserts between the mesh and after inserts, at the unit's output stabilizing area. The working part of the installation included a system of several small-mesh grids 4 (the number varied from 1 to 10). The operational area had a diameter of 0.05m and was transferring into a stabilizing area with the same diameter and then was connecting to the intake portion of centrifugal fan 5.

In the working area between the grids, the probe moves in the Diametric direction perpendicular to the channel wall. The electrical signal is transmitted from the thread to the secondary voltage measuring device. Measurements of averaged velocities with a heat loss anemometer were compared in the available cross-section with the speed measurement with a Pitot tube. The resistance in the experimental section was measured by the difference in static pressure on the channel walls using micromanometers. Drainage holes of 5×10^{-4} m in diameter were used to measure the static pressure, which were located in different sections of the operational area of a tube, inside the porous inserts in between meshes and after inserts at the output stabilizing area of the unit. With the help of the hydraulic press, metal meshes made from L-68 brass were equally pulled onto the base represented by steel rings with an inner diameter of 0.05 m and then were glued to the base.

All materials and tools, including the experimental setup, embedded grid, Pitot tube, micro manometers, Vitoshinskiy nozzle (profiled jet) and traverse gear, with gauges with needles and wollastonite threads of different diameters of platinum, including heat loss-anemometer – assembled and made in the laboratory of mechanics and mathematics faculty of Al-Farabi Kazakh-National University (Almaty, Kazakhstan).

Measurement of an average speed and impulse characteristics of airflow was performed with a heat loss anemometer set to the constant temperature value. A constant temperature anemometer was used. The linearizing chain was based on the principle of nonlinear resistances. This method was developed at al-Farabi Kazakh-National University (Almaty) and is more accurate. The thermoanemometric method used is based on measuring the dependence of the heat transfer of a heated filament on the gas velocity, temperature, and composition. During forced convection, the intensity of heat transfer was determined by gas flow speed around the

heated sensor thread (Wałowski *et al.*, 2017). Anemometer's gauge's body is a brass cylinder of 2×10^{-4} m in diameter and length of 0.115 m. From the body of a gauge, stems are coming out at 0.015-0.018 m distance, made of ordinary steel needles, and with platinum Wollaston wires of 6×10^{-6} soldered to their ends. Heat loss anemometer was put into the channel through special holes inside the measuring rings made from 0.10 m thick acrylic glass and a micrometer screw with a 1×10^{-5} m movement rate. This screw was steadily secured to the acrylic glass ring via two bolts. Two steel needles protrude from the sensor housing at 0.015 – 0.018 m. a Wollaston platinum wire with a diameter of 6×10^{-6} m was soldered to the points of these needles. (6 microns). In experiments with background noise elimination to a minimum (the measurement of ripple derivatives, the study of spectra), the filament diameter was 1×10^{-6} m (1 - micron with a 40-micron shell). The working section of the thread with a length of 1.5×10^{-3} m was located perpendicular to the sensor body, pre-etched with 80 % nitric acid solution, and served as a sensitive element of the sensor. In the experiments, were used threads from the removal of internal stress when examining in the microscope were straight with no tension. Immediately before the measurements, the sensor with a thread was calibrated on a separate installation with a low degree of turbulence, and the dependence of E (mV) on the value of h (torr) was determined, i.e., the speed of the averaged flow. Direct calibration of the sensor with the thread does not require knowledge of the law of heat exchange between the thread and the airflow. It is not necessary to assume that the thread is cooled by a normal (perpendicular) component of the airflow, and the measurements are free from systematic error. The sensitivity of the thread is the same as that determined in the calibration nozzle with a low turbulence level. But there are still a number of sources of measurement errors that are characteristic of this thread and related electrical circuits of the secondary device. The unit was located inside the laboratory and operating in drain mode. Air was fed directly from the room environment and purified from various mechanical particles through a small-cell volume filter that was immediately connected with the nozzle. The operation of a unit assembled using the scheme mentioned above allowed to exclude the margin of measurement error for a gauge of heat loss anemometer, which was present due to the heating of an operating fan and excluding the airflow.

Pressure differences within the Vitoshinskiy nozzle defined the average consumption speed of airflow. At the inlet, the widest section of a nozzle, the pressure was considered equal to atmospheric pressure. The diameters between the widest and the narrowest (equal to pipe diameter) sections of the nozzle were equal to three. The nozzle for average airflow speed within the direct flow pipe was calibrated at the distance of 0.10 m away from the nozzle. Calibration is the comparison of measurement values delivered by a device under test with those of a calibration standard of known accuracy (Faison *et al.*, 2004). Simultaneously, the pressure difference within the nozzle was measured utilizing the inclined micro manometer, whereas average speed profiles within the pipe were measured by heat loss anemometer gauge. Throughout the experiment, consistency of flow rate and flow temperature remained the same, controlled by a 0.1 K precision thermometer. Each time before initiation of the experiment, heat loss anemometer gauges were calibrated within the potential flow. The field of speed was uniform, and the level of impulses was not exceeding 0.5%. The degree of research data repetition was checked in all cases of every experiment, maintaining a highly isobaric and isometric process.

Meshes within sets were installed in a parallel manner, one after another, maintaining a certain distance in between. Values of geometric characteristics of the meshes and packs used within the operational area of the experimental unit, as well as pore volume ε and specific surface area a calculated according to Equation 1, are presented in Table 1. Digit in the first column describes the amount of meshes for a specific model marked with a Greek letter. Digit in the third column describes the distance between meshes within a pack.

3. RESULTS AND DISCUSSION:

3.1 Hydraulic Resistance of Porous Inserts

According to the results of processing data obtained from experiments on single mesh resistance and resistance of packs with identical meshes in terms of values of equivalent resistance coefficient (Equation 2), where Δp – pressure difference on a mesh or pack of mesh with h thickness; pore amount ε and specific surface area " a " are according to Equation 1 and Reynolds equivalent criteria (Equation 3). During the study (Kukes *et al.*, 1981), universal dependence was obtained using Equation

(Equation 4). Proportionality coefficients for meshes considered a regular system were defined in (Kukes *et al.*, 1981) and equal to $C_1 = 44.2$ and $C_2 = 0.35$.

Figure 2 shows the dependence of pressure difference present at meshes under the flow feed speed above average. The resistance of $9\alpha. 5$; $9\alpha. 15$; $9\beta. 5$; $9\beta. 15$. Fifteen packs with the same amount of meshes almost do not depend on the distance between them, corresponding with conclusions on the experiment (Kukes *et al.*, 1981; Yershin and Khadieva, 1988). The conversion of this data into hydraulic resistance values is shown in Figure 3. A continuous line is described using dependence (Equation 4). The maximum deviation of experiment points from the calculated curve I do not exceed $\pm 9\%$. Relative errors in defining the equivalent Re is not more than 4%. Figure 4 shows the pressure distribution within a tube with a porous insert consisting of ten fine meshes accordingly $10\alpha. 15$ and $10\beta. 15$, whereas the Re value equals 49800. Comparing pressure gradients with similar dense pack (continuous straight lines) confirms that the distance between meshes has almost no influence on pressure drop within the pack.

3.2. The Flow Structure in the Channel with Porous Insert Made of Fine Meshes

Figures 5 and 6 show profiles of the longitudinal element of averaged speed referred to as an average feed speed of flow, and distribution of intensity for longitudinal turbulent speed impulses within various sections of a tube with a porous insert made from fine meshes $10\alpha. 15$ and Re value = 49800. It is clear that the initial, rather sharp shaped, speed deforms profile and becomes less sharp as it comes closer to the insert. It happens due to the deceleration of flow before the local resistance, created by a pack of fine meshes. Having completely verified the theory, flattening of the flow was performed due to deceleration of a flow within the axis area and redistribution of some portion of flow towards the outer area because of the transverse gradient of pressure before the fine mesh pack. It should be noted that the porous insert represented by the fine meshes pack used during the experiment has rather low hydraulic resistance necessary for flattening the flow speed profile before the meshes pack, which was mentioned in paper Min *et al.* (2017).

Decrease of turbulence impulses intensity near the wall of a tube, according to Figure 6b, is based on the acceleration of flow within this area of a channel, whereas in the middle portion of a

tube, it decreases rather slower due to flow deceleration. In all experiments with no exception, measurements were taken from two set distances between meshes ($15 \times 10^{-3} \text{ m}$ from two set distances ($5 \times 10^{-3} \text{ m}$ and $1 \times 10^{-2} \text{ m}$ accordingly) from each of ten meshes. That is why two profiles obtained demonstrate the situation immediately after a mesh and flow condition reaching the next mesh.

Figure 6 shows data of measurements taken after the first and the second meshes. This and the following figures have profiles of the longitudinal component illustrated in the top section and distribution of turbulence intensity in the bottom section (Equation 5). It is still possible to define signs of initial nonuniformity of flow field in the profile of the average speed of the flow coming through the first mesh (Figure 6a). However, these profiles were heavily deformed at that moment. Impulse components behind the first mesh are close in their values to those of an approaching flow. However, with the increase of distance to a mesh, turbulence decrease, as shown in Figure 6b). After the second mesh (Figure 6c), the average turbulence value was equal to 5-6%, and after the third mesh (Figure 6d), it went down to 3%. Profiles of averaged speed after the second mesh are considered to be almost uniform and equal.

Performed experiments show that during the passage of the flow through the first mesh, mesh turbulence with a much smaller scale is placed at the top of the initial large-scale turbulence, even though the first mesh, due to its high degree of pore volume, which also means lower resistance, is not capable of making sufficient changes to the turbulence structure of the flow, generates a larger amount of low-scale turbulence. After the second mesh, such isotropy increases, but some residual effects can still be observed. After the third mesh, there is almost none left from initial large-scale turbulence, and the flow is defined by low scale mesh turbulence, which tends to vanish. Starting from the third mesh and up to the tenth mesh, the distribution character of averaged and impulse speeds is not changing. Profile of averaged speed remains flat "stem", and impulse speed has periodic nature: after each mesh, the degree of impulse was equal to 4-5% and was defined by mesh characteristics. The mesh turbulence tends to vanish and drops down to 3% before the next mesh.

The fact that low scale mesh turbulence trends to vanish can be observed well in sections behind a porous insert. The comparison of

averaged speed profile and turbulence distribution profile within a mesh pack and after the last tenth mesh insert looks identical in the first two sections. In the following sections, profiles of averaged speed are rather flattened already and do not change much, whereas low scale isotropic turbulence continues to vanish and decreases to 0.9%, which means that the flow is cleaning gradually. In this portion of a channel, the generation of turbulence and further development of the border layer on inner tube walls takes place.

There were obtained similar experiment results data for 10α . 15 pack under $Re = 15120$ and average speed of $UAV = 4.9 \text{ m/s}$. Hydraulic resistance of 10α . 15 mesh pack is much lower, almost 10 times lower than the one under $Re = 4980$. A comparison of experimental results for both flow modes ($Re = 4980$ and 15120) shows the similarity of flow development trends, but with the decrease of ΔP . Simultaneously, it is clear that averaged speed profiles have a rather non-uniform nature. However, their mesh turbulence is still prevailing, leading to the growth of flow isotropy. After the third mesh, averaged profiles of longitudinal speed components become almost uniform, and turbulence intensity changes as periodically as under $Re = 4980$.

One of the peculiarities of turbulence behavior within the porous layer of meshes is that turbulence intensity decreases as the flow comes closer to the insert and significantly decreases in immediate proximity to meshes connected with the "cleaning" effect of fine mesh. A fast drop of turbulence intensity also verifies such phenomena after the first two meshes due to the stabilizing effect of fine meshes and suppressing the overall swirling of the flow. What happens is the division of initial large-scale turbulence and simultaneous generation of its mesh turbulence. Simultaneously, a turbulent state of the flow that can be observed after the first mesh depends on turbulence level before this mesh. And only starting from the third mesh and all the way to the tenth mesh, the nature of turbulence changes is stabilizing. Each mesh increases the degree of impulses by 4-5% on average, but this value drops to 3% before the next mesh since turbulence created by the structure are vanishing as they grow distance from it. Based on the studied experiment results, it was considered that the distance between meshes has virtually no influence on pressure drop. Therefore, the complete pressure difference within the meshes set is equal to the sum of pressure difference within composing meshes. One of the biggest

advantages of airflow measurement using heat loss anemometer is the possibility of studying the flow characteristics on rather low speed and the low margin of error (Khintse, 1963; Kukes *et al.*, 1981).

Vanishing of large-scale turbulence on porous insert made of ten smaller meshes 10α . 15 happens faster due to its dense netting. After the third mesh flow stabilizes itself and after each mesh, the degree of turbulence increases and then decreases before the upcoming mesh and equals about 1%. Measurements results under lower Reynolds values have shown similar peculiarities of flow within the porous layer of meshes. Thus, based on obtained experimental results, it can be said that within the porous layer made of fine meshes after the third mesh system reaches the balance between generation and dissipation of turbulence energy. On average, turbulence intensity remains at the same level, which depends on the speed of airflow (Re value) and geometric characteristics of meshes (M/d parameters). Such behavior of turbulence energy takes place in the case of the grainy layer, which was shown in work (Kreindel' *et al.*, 1984), where authors were measuring averaged speed and turbulence intensity in gaps between each of 10 rows of spheres packed in the form of the cube. The measurements give a reason to think that turbulence characteristics generated by each mesh depend on its coefficients of resistance, Equation 6.

Indeed, turbulence energy appears due to work performed by airflow and strives to overcome this resistance. It should be noted that if mesh would be considered as the unit, which transforms intake turbulence (before mesh) (Equation 7) into exhaust turbulence (after mesh) (Equation 8), then the turbulence transformation coefficient (Equation 9) for each mesh in the pack, starting from the third mesh would be equal to Equation 10. According to Dryden and Schubauer theory (Van der Merwe and Gauvin, 1971). In that case, the decrease of longitudinal turbulence (Equation 8) using mesh happens under the following Equation 11. Experiments confirmed such a theoretical conclusion by these very authors (Van der Merwe and Gauvin, 1971). Table 2 contains ξ values and turbulence transfer coefficients, which were calculated using our experiment data. As is seen from Table 2, values Equations 9 and 10 differ from one another by not more than 6%.

Based on the experiments performed, the following conclusion could be made: when liquid moves within the porous environment, there

appears some isotropic turbulence, characteristics of which are defined by flow conditions and size of pores. Analysis of obtained data, with a high degree of validity, shows that turbulence created by mesh, vanish within the space between meshes and do not continue its movement towards the mesh located further down the flow. A similar conclusion can be made due to the results of experimental researches performed by other authors (Manshadi, 2011; Wałowski and Filipczak, 2017). These researches also state that the formation of swirls in some pore cells do not travel to neighboring cells but completely vanishes in the initial cell. Therefore, it may be said that the generation of turbulence energy and its dissipation within the isotropic porous environment is in the local balance.

4. CONCLUSIONS:

Thus, they were obtained from experimental data and results on hydraulic resistance of incompressible liquid (air) movement in a circular tube with porous inserts made from cartridge packs with fine meshes. Experiments carried out show that, during the passage of the flow through the first mesh, mesh turbulence with much less size is put on top of the initial large-scale turbulence, while the first mesh is not capable of making significant changes in the turbulence structure of a flow due to its high pore volume, which also means lower resistance, it produces a greater amount of low-scale turbulence.

Starting from the third mesh and up to the tenth mesh, the distribution character of averaged and impulse speeds is not changing. Immediately before fine meshes, the speed profile becomes flatter. Profile of averaged speed remains flat "stem", and impulse speed has periodic nature: after each mesh, the degree of impulse was equal to 4-5% and was defined by mesh characteristics, then the mesh turbulence trends to vanish and drops down to 3% before the next mesh. After porous inserts and fine meshes, the turbulent structure of flow changes itself. The experiment shows a local balance between generation and dissipation processes within porous inserts made from fine meshes. On average, turbulence intensity remains at the same level, which depends on the speed of airflow (Re value) and geometric characteristics of meshes (M/d parameters).

5. ACKNOWLEDGMENTS:

This research is funded by the Science Committee of the Ministry of Education and Science of the Republic of Kazakhstan (Grant No. AP05133388).

6. REFERENCES:

1. Astanovskii, D., and Astanovskii, L. (2005). Reactor for catalytic processes under optimal temperature conditions. *Chemical and Petroleum Engineering*, 41, 513-521. <https://doi.org/10.1007/s10556-006-0011-7>
2. Bhattacharjee, S., Roy, D., and De, S. (2019). *Hydrodynamics of electroosmotic flow in a microchannel with porous wall*. Retrieved from <https://arxiv.org/abs/1902.04068>
3. Ershin, Sh. A., Zhabbasbaev, U. K., Kulymbaeva, M.Sh., and Khadieva, L.G. (1990). Investigation of aerodynamics of apparatus with a stationary packed bed. *Applied Mechanics and Technical Physics*, 4, 124-232.
4. Esakov, Y. P., and Kotelkin, V. D. (1986). Hydrodynamic model of a reactor with a stationary catalyst bed. *Doklady. Chemical Technology*, 289–291, 106–109.
5. Evtushenko, A. I., and Kotelkin, V. D. (1991). Modelling of transport processes in fixed granular bed. *Teoreticheskie Osnovy Khimicheskoi Tekhnologii*, 25, 511–523.
6. Faison, C. Douglas; Brickenkamp, and Carroll S. (2004). Calibration Laboratories: Technical Guide for Mechanical Measurements. In *NIST Handbook 150-2G*. Gaithersburg: National Institute of Standards and Technology.
7. Genbach, A., Olzhabaeva, K., and Iliev, I. (2016). Boiling process in oil coolers on porous elements. *Thermal Sciences*, 20(5), 1777-1789. <https://doi.org/10.2298/TSCI150602166G>.
8. Goldshtik, M. A. (1985). Variational model of a turbulent rotating flow. *Fluid Dynamics*, 20, 353–362.
9. Khintse, I. O. (1963). *Turbulence*. Moscow: Fizmatgiz.
10. Kirillov, V. A., Kuz'min, V. A., P'yanov, V. I., and Khanaev, V. M. (1979). Velocity profile in a fixed granular bed. *Reports of the Academy of Sciences of the SSSR*, 245, 159-167.
11. Kreindel', I. Y., Sergeev, S. P., Dil'man, V. V., and Nazarov, A.S. (1984). Spreading of a gas stream before a granular catalyst bed. *Theoretical Foundations of Chemical Engineering*, 18(5), 415-419.
12. Kukes, V. I., Ufimtsev, A. A., and Yarin, L. P. (1981). Optimizing a thermoanemometric experiment at low and high turbulence intensities. *Journal of Engineering Physics*, 40, 581–584.
13. Maciel, H. E., and Camara, L. D. T. (2019). Non-darcy flow evaluation of unconsolidated porous media in a closed-loop permeameter. *Revista da Engenharia Térmica*, 18(2), 78-84.
14. Manshadi, M. (2011). The Importance of Turbulence Reduction in Assessment of Wind Tunnel Flow Quality. Retrieved from <https://www.intechopen.com/books/wind-tunnels-and-experimental-fluid-dynamics-research/the-importance-of-turbulence-reduction-in-assessment-of-wind-tunnel-flow-quality>
15. McSherry, R., Chua, K., Stoesser, T., and Falconer, R. A. (2016). Large eddy simulations of rough bed open channel flow with low submergence and free surface tracking. *River Flow - Proceedings of the International Conference on Fluvial Hydraulics, RIVER FLOW, 2016*, 85-90.
16. Min, J. H., Jeong, W. L., Kwak, H. M., and Lee, D. S. (2017). High-performance metal mesh/graphene hybrid films using prime-location and metal-doped graphene. *Scientific Reports*, 7, Article number 10225.
17. Sergeev, S. P., Dil'man, V. V., and Genkin, V. S. (1974). Distribution of streams in channels with porous walls. *Journal of Engineering Physics*, 27, 1180–1185 <https://doi.org/10.1007/BF00864011>
18. Showkat Ali, S. A., Azarpeyvand, M., and Ilário da Silva, C. R. (2017). Boundary layer flow interaction with porous surfaces. In *Proceedings of the 24th International Congress on Sound and Vibration (ICSV 2017)*. London: International Institute of Acoustics and Vibration.
19. Vaisman, A. M., and Goldshtik, M. A. (1978). Dynamic model of liquid motion in a porous medium. *Fluid Dynamics*, 13, 864–869.
20. Van der Merwe, D. F., and Gauvin, W. H. (1971). Velocity and turbulence measurements of airflow through a packed

bed. *AIChE Journal*, 17(3), 519-528.

21. Vlasov, O. A. (1991). Investigation of the aerothermochemical process in a fixed-bed catalytic reactor. *Fluid Dynamics*, 26, 252-258.
22. Volkov, S. A., Reznikov, V. I., Zel'venskii, V. Y., and Khalilov, K. F. (1984). Cross-sectional nonuniformity in a fixed granular bed and linear diffusion. *Theoretical Foundations of Chemical Engineering*, 18, 394-401.
23. Vortmeyer, D., and Schuster, J. (1983). Evaluation of steady flow profiles in rectangular and circular packed beds by a variational method. *Chemical Engineering Science*, 38, 1691-1699.
24. Wałowski, G., and Filipczak, G. (2017). Klinkenberg effect in hydrodynamics of gas flow through anisotropic porous materials. *E3S Web of Conferences*, 19, Article number 03008.
25. Yershin, Sh. A., and Khadieva, L. G. (1988). Hydraulic resistance and refracting effect of a fine-mesh screen. *Fluid Dynamics*, 23, 249-254.
26. Yushko, S. V. (2015). Turbulent stationary gas flow in the Vitoshinsky nozzle, results of studies of integral flow characteristics. *Technological University Bulletin*, 19, 125-126.
27. Zhizhkin, A., Lazutkin, G., Davydov, D., and Volkova, T. (2018). Influence of Porous Material MR Structure on its Flow Characteristics. *IOP Conference Series: Materials Science and Engineering*, 302, Article number 012074.

$$\varepsilon = 1 - \frac{\pi d}{4(b+d)}, a = \frac{\pi}{b+d}. \quad (\text{Eq. 1})$$

$$\xi_e = \frac{\Delta p}{h} \left(\frac{a}{\varepsilon^3} \frac{\rho u_{cp}^2}{2} \right)^{-1}, \quad (\text{Eq. 2})$$

$$\text{Re}_e = \frac{u_3 d_3}{\nu} = \frac{4 u_{cp}}{\nu a}. \quad (\text{Eq. 3})$$

$$\xi_e = \frac{C_1}{\text{Re}_e} + C_2. \quad (\text{Eq. 4})$$

$$\sqrt{u'^2}/u \quad (\text{Eq. 5})$$

$$\xi = 2\Delta P/(\rho u_{av}^2), \quad (\text{Eq. 6})$$

$$(\sqrt{u'^2}/u), \quad (\text{Eq. 7})$$

$$(\sqrt{u'^2}/u)_+, \quad (\text{Eq. 8})$$

$$(\sqrt{u'^2}/u)_+ / (\sqrt{u'^2}/u_-), \quad (\text{Eq. 9})$$

$$\sqrt{1 + \xi}. \quad (\text{Eq. 10})$$

$$1/\sqrt{1 + \xi}. \quad (\text{Eq. 11})$$

Table 1. Geometric parameters of meshes

Mesh amount	Wire diameter $d \times 10^3$, m	Distance in between meshes, mm	Distance in between wires, $b \times 10^3$, m	Mesh cell size, $m \times 10^3$	Pore amount, ε	Spec. surf. area, a , m^{-1}	Equiv. diam., $d_3 \times 10^3$, m
α	0.40		0.88	1.28	0.755	2453	1.23
3 α	0.40	5	0.88	1.28	0.755	2453	1.23
9 α	0.40	5	0.88	1.28	0.755	2453	1.23
9 α	0.40	15	0.88	1.28	0.755	2453	1.23
10 α	0.40	15	0.88	1.28	0.755	2453	1.23
β	0.15		0.25	0.40	0.706	7850	0.36
3 β	0.15	5	0.25	0.40	0.706	7850	0.36
9 β	0.15	5	0.25	0.40	0.706	7850	0.36
9 β	0.15	15	0.25	0.40	0.706	7850	0.36
10 β	0.15	15	0.25	0.40	0.706	7850	0.36

Table 2. ξ values and turbulence transfer coefficients

Porous insert code	Re	u_{av} , m/s	ξ	$\sqrt{1 + \xi}$	$(\sqrt{u'^2}/u) + / (\sqrt{u'^2}/u) -$
10 α . 15	49800	15.9	1.73	1.65	1.56
10 α . 15	15120	4.9	1.87	1.69	1.60
10 β . 15	49800	15.9	3.03	2.01	1.95
10 β . 15	15120	4.9	4.02	2.24	2.18

Figure 1. Experimental setup: 1 – vitoshinskiy profiled jet, 2 – main channel, 3 – shaped honeycomb, 4 – system of several small-mesh grids, 5 – centrifugal fan

Figure 2. Dependence of pressure difference in a pack with identical meshes on average flow feed speed

Figure 3. Dependence of equivalent resistance coefficient on Reynolds value for packs with identical meshes

Figure 4. Distribution of pressure along the tube with a porous insert made from ten fine meshes with $Re = 49800$

Figure 5. Illustrates the flow speed and turbulence intensity of a porous insert made of ten fine meshes 10α 15 located on a different distance from one another under $Re = 49800$

The first (a,b) and the second (c,d) meshes at the distance of: a,b – 5×10^{-3} m, c,d – 1×10^{-2} m under $Re=49800$

Figure 6. Profiles of longitudinal speed component and distribution of turbulence intensity inside the porous insert $10\alpha. 15$