SPREADING OF A FLUID JET ON THE CORRUGATED SURFACE OF THE STRUCTURED PACKING OF WET SCRUBBERS

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Abstract. The new packing for wet scrubbers for cooling exhaust gases of furnaces is presented. Spreading features of the fluid jet on the corrugated surface of the proposed packing have been studied. Flow rate of the liquid flowing through slits to the opposite side of the packing element was determined. Several regimes of a fluid flow on the surface of the proposed structured packing were determined. An optimal range of rational flow rates for more intense cooling of exhaust gases is proposed. It was discovered that the range of optimum flow rates may be extended if the surface of the packing element is pre-wetted. The way of increasing the rate of effective interfacial surface area for gas-liquid contact per unit volume of the packing of the scrubber is presented.
Keywords: structured packing, fluid film, heat and mass transfer, wet scrubber, exhaust gases, waves.

REVĂRSARE A JETULUI DE LICHID PE SUPRAFAŢA DUZEI REGULARE A ECONOMIZORULUI DE TIP CONTACT

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Rezumat. Se propune o nouă soluţie constructivă de realizare a duzei pentru economizoarele de tip contact. Sunt cercetate caracteristicile de revărsare a jetului de fluid pe suprafaţa duzei propuse. Sunt obţinute date experimentale privind cantitatea de lichid care este în scurgere gravitaţională pentru pelicula de lichid pe elementul duzei şi care curge pe partea ei opusă prin perforaţia din duză. Se demonstrează, că există mai multe regimuri de curgere a fluidului pentru realizarea propusă constructivă a duzei. S-au formulat recomandări privind diapazonul optim de debite de lichid pentru utilizarea în economizoare de tip contact. S-a stabilit, că diapazonul optimal de debit de fluid poate fi lărgit prin umezirea prealabilă a elementului, deci a duzei. S-a propus o metodă de majorare a suprafeţei active a duzei în economizor de tip contact.
Cuvinte-cheie: duza regulară, pelicula de lichid, schimb de căldură şi masa, economizor de tip contact, gaze eşapate, unde.

РАСТЕКАНИЕ СТРУИ ЖИДКОСТИ ПО ПОВЕРХНОСТИ РЕГУЛЯРНОЙ НАСАДКИ КОНТАКТНОГО ЭКОНОМАЙЗЕРА

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Аннотация. Предложена новая конструкция насадки для контактных экономайзеров. Исследованы особенности растекания струи жидкости по поверхности предлагаемой насадки. Получены опытные данные по количеству жидкости, которая при гравитационном стекании пленки жидкости по элементу насадки, перетекает через просечки в насадке на противоположную сторону. Показано, что существует несколько режимов течения жидкости по данной насадке. Предложен оптимальный диапазон расходов по жидкости, для использования данной насадки в контактных экономайзерах. Установлено, что оптимальный диапазон расходов жидкости может быть расширен предварительным смачиванием элемента насадки. Предложен способ увеличения активной поверхности насадки в контактном экономайзере.
Ключевые слова: регулярная насадка, пленка жидкости, тепломассообмен, контактный экономайзер, дымовые газы, волны.

1. INTRODUCTION

Partial replace of the exhaust gases cooling in conventional section of the fired heaters and furnaces by cooling the exhaust gases in wet scrubbers can improve energy efficiency and reduce air pollution of power plants. Efficiency of wet scrubbers depends on intensity of heat and mass transfer. That's why one of the actual goals of the power engineering is to increase the efficiency of heat and mass transfer. As a results of heat and mass transfer between exhaust gases and water in a wet scrubber, exhaust gases are cooled and dried. Water can be heated to a high temperature (60-80^{o}C). Also, exhaust gases can be cleaned from many polluters. Design and development of the new structured packings (or fill) is actual task for increasing the efficiency of heat and mass transfer. Many researches are devoted to studying of structured packings for scrubbers, cooling towers and columns [1,2,3]. The high sensitivity of structured packings to the initial liquid distribution is one of the disadvantages of the structured packings. The reason of that is the regime of a fluid flow in heat and mass transfer equipment. Scrubbers work below the loading point, when the liquid spreads as the film on the surface of the structured packing. Velocity of the gas is low and the gas can't distribute the liquid on the surface of the structured packing because the shear stress between the gas and the liquid on the free surface of liquid film in scrubbers with structured packing is too low. That's why scrubbers should have efficient liquid distribution and redistribution systems. However cone spray nozzles are used for liquid distribution very often. Cone spray nozzles sometimes irrigate only one side of the elements of the structured packing. The scheme of the irrigating of the structured packing (any packing from Fig. 1) with spray nozzle is shown on Fig. 2. We can see from the scheme (Fig. 2) that the large part of the element can stay dry in wide range of the liquid flow rates. Dry surface of the packing elements doesn't participate in heat and mass transfer between the gas stream and the falling film of the fluid.

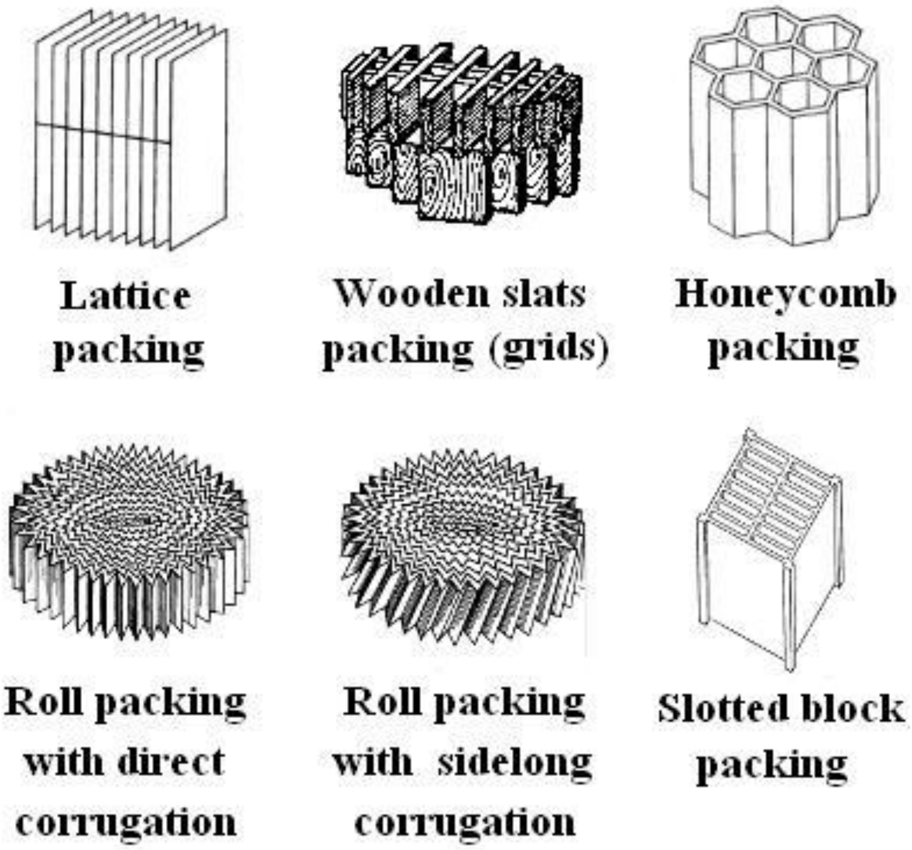

Figure 1. *Various structured packings*

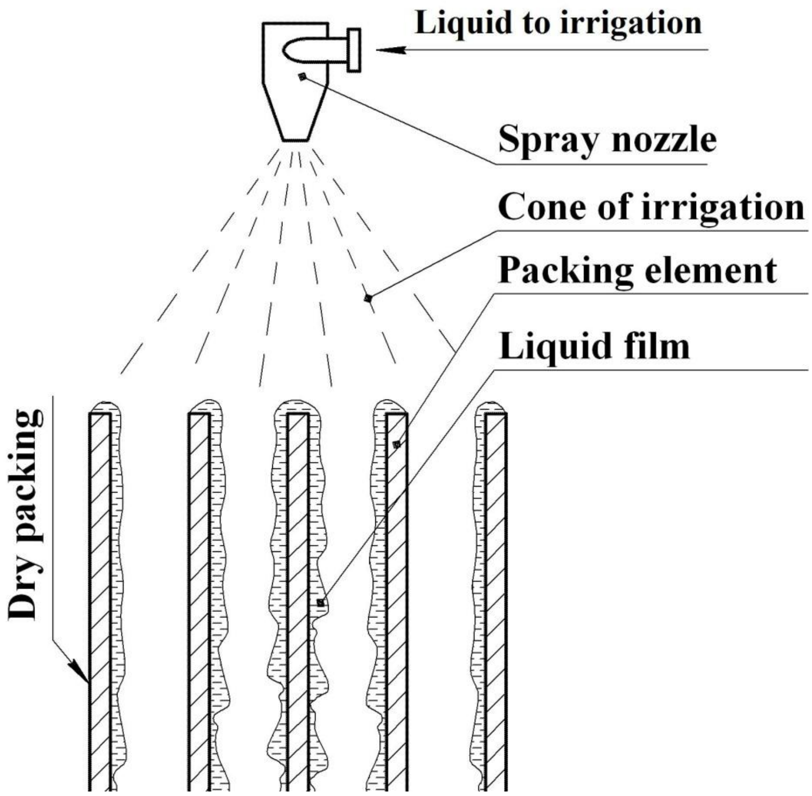

Figure 2. *Irrigation of the structured packing with spray nozzle*

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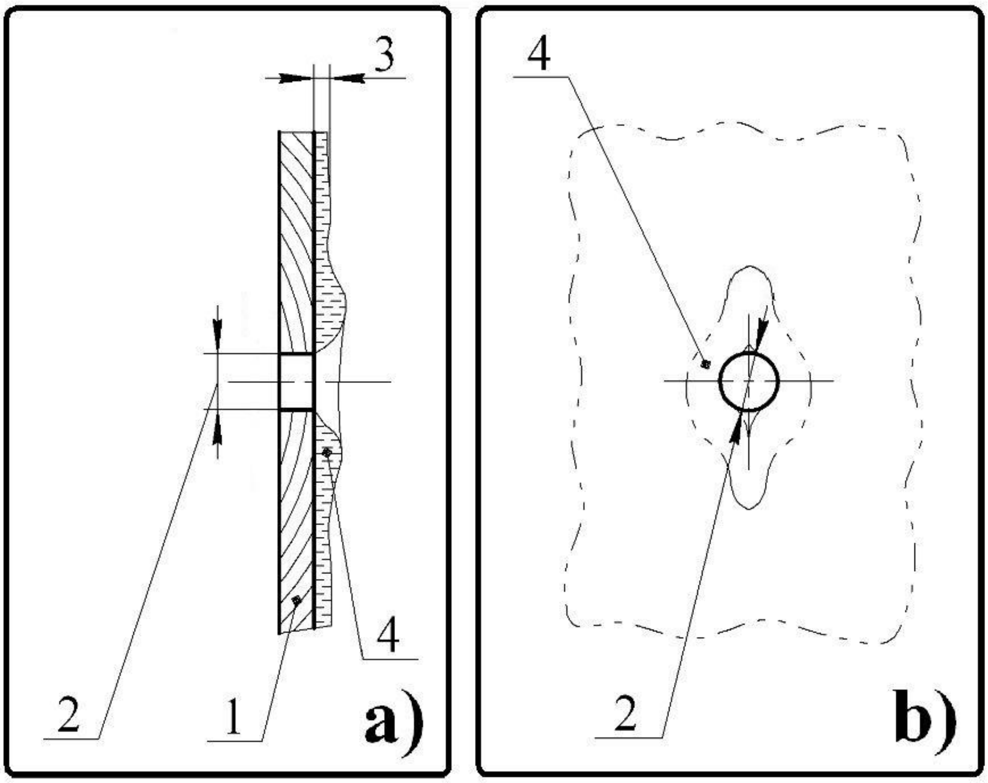

Figure 3. *Scheme of the falling fluid film around cylindrical hole in the packing, a) – longitudinal section, b) – front view; 1 – element of structured packing, 2 – hole in the packing, 3 – thickness of the fluid film, 4 - local increasing of the fluid film thickness*

A perforation of the packing is one of the ways to reduce sensitivity of structured packings to initial liquid distribution. Some portion of the liquid can flow to the opposite side of the packing element through the holes [4]. However geometric surface area per unit volume of the packing *a* (m2/m3) for the perforated packing is lower, than for the packing without perforation. If liquid flow rate is too small or the diameter of the holes is too large, liquid doesn't flow through the holes on the opposite side of the packing element (Figure. 3).The liquid flows around the holes by large jets [4]. These large jets are the reason of local increasing of the fluid film thickness. This local increasing of the liquid film thickness is a reason of increasing the pressure drop of the packing bed because free cross sectional area of the scrubber decreases.

Another way to reduce sensitivity of structured packings to liquid distribution are slits. The difference between slits and holes is that slits are performed without removing the chips from the packing material. Holes are usually performed by using machining operations such as drilling, milling, etc. Slits can be performed both on flat and on corrugated packings. HOLPACK packing [5] is example of the structured packing with slits. An element of the new structured packing is shown on Figure. 4. The packing was designed in Moscow state university of mechanical engineering [5]. An element of the structured packing is made from corrugated aluminum sheet EN AW 3103. Aluminum alloys can be used at high temperature and aluminum is wetted very good. The slits are placed between nearby corrugated elements. Thickness of a billet of the structured packing is 0.25 mm. Height and width of the packing element is 250 mm. Height of corrugation of the packing element is 2.8 mm. Corrugation of the packing elements increases geometric surface area per unit volume of the packing *a*. The packing bed is the several parallel packings elements. A gap between nearby elements of the structured packing is selected in accordance with the fluid film thickness and width of the channel for gas flow.

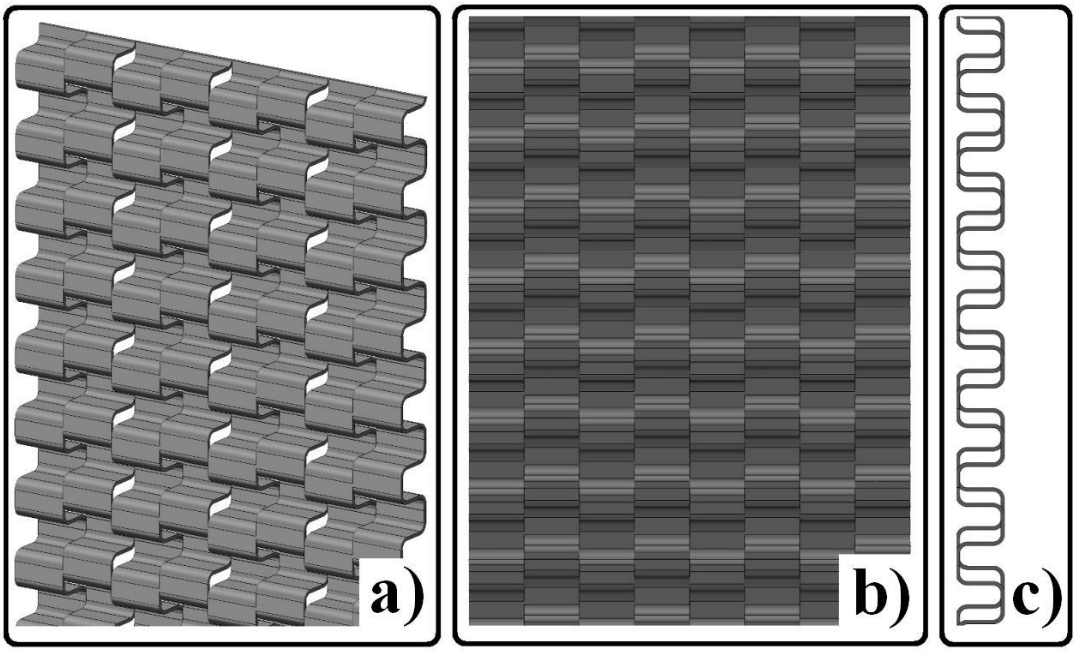

Figure 4. *Element of the structured corrugated packing with slits, a) – isometric view, b) – front view, c) – side view*

The full wetting of a packing is very important for a heat and mass transfer processes between the falling fluid film and gas. To ensure full wetting of the proposed structured packing it is necessary to study the falling features of fluid film on the surface of the packing. Purpose of this article is studying features of fluid film flow to the opposite side of the packing element through the slits between corrugations.

2. FALLING OF THE FLUID FILM

Navier-Stokes equations describe the motion of a fluid. For laminar fluid film (see Fig. 5), Navier-Stokes equations can be rewritten as follows:

$$\rho = (w_x \frac{\partial w_z}{\partial x} + w_y \frac{\partial w_z}{\partial x} + w_z \frac{\partial w_z}{\partial x}) = \frac{\partial p}{\partial z} + \rho \cdot g + \mu \left(\frac{\partial^2 w_z}{\partial x^2} + \frac{\partial^2 w_z}{\partial y^2} + \frac{\partial^2 w_z}{\partial z^2} \right) \qquad (1)$$

Continuity equation for the fluid film is defined as:

$$\frac{\partial w_x}{\partial x} + \frac{\partial w_y}{\partial y} + \frac{\partial w_z}{\partial z} = 0 \qquad (2)$$

As a result of the conversions (1) and (2), we can obtain [6]: или we can obtain in accordance with [6]:

$$g\rho + \mu \frac{\delta^2 w_z}{\delta y^2} = 0 \qquad (3)$$

As a result of conversions we can calculate the thickness (see Fig. 5) of the laminar fluid film from the equations [6,7]:

$$\delta = \sqrt[3]{\frac{3q\nu}{g}} = \sqrt[3]{\left(\frac{3}{4} \frac{\nu^2}{g} \mathrm{Re} \right)} \qquad (4)$$

Medium thickness of the turbulent fluid film can be determined by using equation in the work [8]. If the fluid film falling on the corrugated surface of a pipe, we can use the next equation for the thickness of the fluid film on the peaks of corrugation [9]:

$$\delta_p = \sqrt[3]{\left(0,68 \frac{\nu^2}{g} \mathrm{Re} \right)} \qquad (5)$$

and on the valleys of the corrugation [9]:

$$\delta_v = \sqrt[3]{\left(0.83 \frac{\nu^2}{g} \mathrm{Re} \right)} \qquad (6)$$

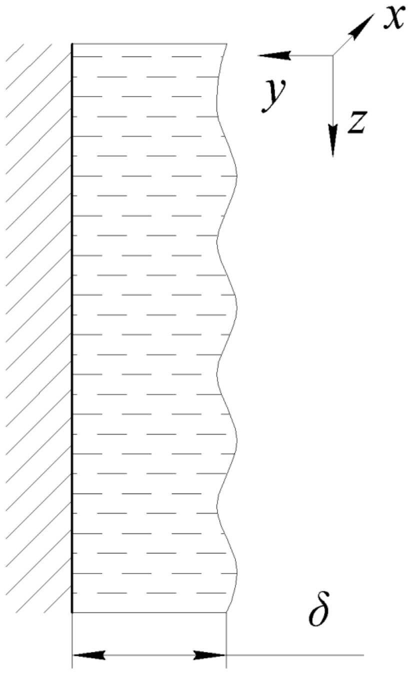

Figure 5. *Scheme of the falling fluid film*

From the equations (3) and (4) we can see, when flow rate increases, thickness of the fluid film on the valley of the corrugation increases faster, than thickness of the fluid film on the peak of the corrugation. As a result of analysis of the equation, we can expect that free surface of the fluid film will be flat at some flow rate. But the equations (3) and (4) don't consider dimensions of the corrugation and cannot be used for engineering calculations. In the work [10], authors collected large experimental material about medium thickness of the fluid film in the pipes with various shapes of roughness. However equation from the work [10] can be used only for falling of the fluid film in the pipes (or on the pipes) with large Reynolds numbers. In the work [11] authors present some experimental results concerning fluid film thickness on the flat surface of the structured packing with roughness. The shape of the roughness is horizontal valleys. We can see theoretical research of the falling fluid film in the work [12].

If the fluid film is falling on the perforated surface, some portion of the fluid can flow to another side of the surface. Author [4] affirms that shape and dimensions of the holes influence much on the flow of the fluid film to another side of the surface. Other researches about flow of the fluid film on the perforated packing have not been found in the public press.

3. EXPERIMENT

For the experiments authors made the experimental stand (see Figure. 6). On the base 1 we fixed the element of the structured corrugated packing with slits 2 so that the corrugation was horizontal. We used water with temperature 11^{o}C for irrigation. The water was fed by the single jet through the inlet nozzle 3 on the top of the packing (diameter of the inlet nozzle was 6 mm). Flow rate of the liquid L_t was changing from 4,5 ml/s to 25 ml/sec. The liquid was fed only on the front side of the packing elements. The reflecting sheet 4 was fixed to the top of the packing element for reflecting the fluid jet, splashes and droplets. The reflecting sheet 4 did not allow the liquid to flow on the back side of the packing element at the moment of contact the jet of fluid with the packing element. The water was collected in the beakers 5 and 6 (for determine flow rate per second) after runoff from the packing element. We determined the flow rate of the liquid, collected from the front side of the packing element L_{fr}, the flow rate of the liquid, collected from the back side of the packing element L_b and the total flow rate L_t by using the beakers 5 and 6. For calculation portion of the liquid X entered through the slits from the front side of the packing element to the back side of the packing element (number of reflow) we used equation:

$$X = \frac{L_b}{L_t}.$$

The dimensionless quantity X can be used for evaluation of the efficiency of liquid's distribution in the structured packings.

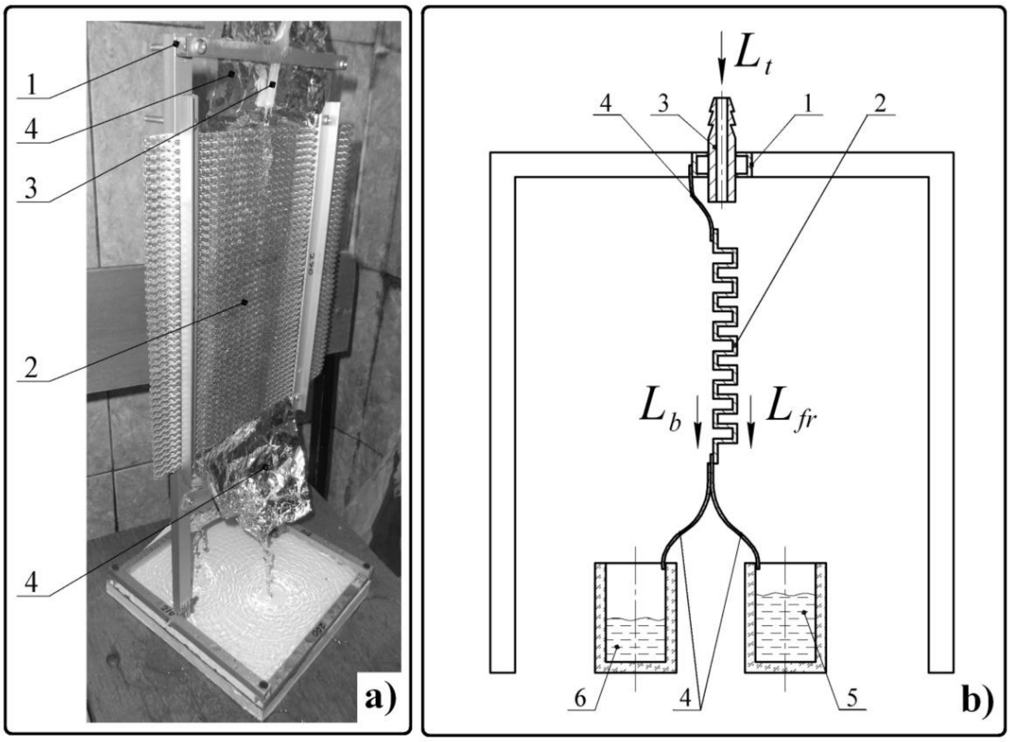

Figure 6. *Experimental setup a) – isometric view; b) – scheme; 1. base, 2. packing element, 3. inlet jet nozzle, 4. impingement sheets, 5, 6. beakers, L_t – liquid for irrigation, L_{fr} – liquid, collected from the front side of the packing element, L_b – liquid, collected from the back side of the packing element*

4. RESULTS AND THEIR DISCUSSION

Liquid from the inlet nozzle was flowing in the form of the single droplets with the flow rate L_t < 4,5 ml/s. When the flow rate was: L_t > 25 ml/s liquid from the inlet nozzle was breaking into many splashes and droplets at the moment of contact the fluid jet with the top of the packing element. When the flow rate was in the range of 4,5 ml/s < L_t < 25 ml/s the liquid jet was transforming into a liquid film with a certain width. Four different regimes of the falling of liquid film on the packing surface were determined in this range of flow rates:

1. Flow regime with partial wetting;
2. Front side flow regime with "standing waves";
3. Both sides flow regime with "standing waves";
4. Flow regime with flooding.

First regime with partial wetting started when the flow rate was L_t < 4,5 ml/s. Corrugation peaks of the packing surface stayed dry in this regime. The fluid was spreading in horizontal direction in valleys of corrugation. In vertical direction, fluid film was falling through slits (Figure. 7a). The flow rate of the liquid flowing down from the back side of the packing element L_b was approximately equal the flow rate of the liquid flowing from the front side of the packing element L_{fr}. In addition, this regime of the fluid falling is not rational for using in scrubbers because only the small part of the packing element's surface is wetted. Remaining dry surface of the packing element does not participate in heat and mass transfer between gas and liquid.

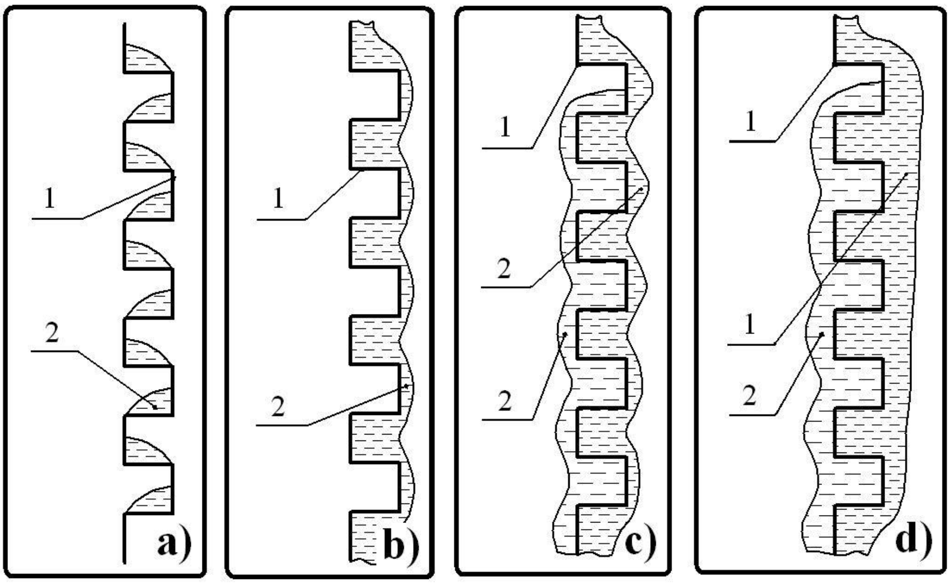

Figure 7. *Scheme of the liquid flowing on the surface of the packing element in different wetting types: a) flow regime with partial wetting; b) front side flow regime with "standing waves"; c) both sides flow regime with "standing waves" d) flow regime with flooding. 1. element of structured corrugated packing with slits; 2. fluid*

We can use Reynolds number Re of the fluid film to represent the range of this regime falling of liquid:

$$\mathrm{Re} = \frac{4q}{\nu}$$

where:

$$q = \frac{L_t}{b}$$

But, flow rate in first regime is too small, that we could not determine the width of the fluid film in this regime. We can't determine q and Re without width of the fluid film.

Next regime of the fluid film falling begins when flow rate $L_t > 4.5$ m^3/hour. Authors call this regime front side flow regime with "standing waves". Waves are formed on the free surface of fluid film (see Figure. 7b). Kholpanov L.P. and Shkadov V.Ya [13] use the term "standing waves" for waves, formed on rough surfaces, when the height of the profile peaks matches the thickness of the fluid film. The fluid film repeats profile of the irregularities and forms the regular waves when the fluid film is falling on a rough surface. The length of these waves (distance between nearby peaks of these waves) depends on the distance between nearby profile peaks. The number of "standing waves" matches the number of the profile peaks under the fluid film. The difference between gravity waves and "standing waves" is that the gravity waves are move down on the surface of the fluid film. "Standing waves" don't move. The position of the peaks and valleys of "standing waves" coincide with the peaks and valleys of the roughness. The proposed structured packing has no roughness – the height of the profile peak is smaller than the thickness of the fluid film. On this structured packing, standing waves appear as a result of corrugation of the packing element.

The fluid film is not formed on the opposite side of the packing element in this regime. The fluid is not flowing on the opposite side of the packing element through the slits. The reason is that width of the slits is too small (0,001 m). Capillary forces kept the fluid in the slits. Authors watch meniscuses of the fluid in the slits from the back side of the packing element. We suppose if external forces act to the fluid, it starts to flow through the slits on the back side of the packing element. External forces should be more than capillary forces. Examples of external influence are turbulence in the fluid film, vibration of the packing element, fluctuation of the packing element or the flow rate, reduction of the fluid viscosity and surface tension of the fluid as a result of heating (or adding of surfactants). For this regime maximum value of flow rate is 15 ml/s. Maximum value of Reynolds number can be calculate using next equation:

$$\mathrm{Re} = \frac{4q_{2-3}}{\nu} = 575$$

where $q_{2\text{-}3}$ = $1.875 \cdot 10^{-4}$ $m^3/m \cdot s$ – maximum value of volumetric flow rate per width of the fluid film for the second regime of the fluid film falling.

Third regime of falling fluid film starts if flow rate of the liquid L_t is more than 15 ml/s. Authors call the third regime both sides flow regime with “standing waves”. In this regime fluid starts to flow intensively through the slits to the back side of the packing element. The fluid film is formed on the both sides of the packing element (see Figure. 7c). Authors suppose that the fluid starts to flow through the slits of the packing element because turbulence appears in the fluid. The fluid film with high velocity presses fluid through the slits in the packing element to the opposite side. In Fig. 8 is shown that the X grows with L_t in the range of flow rate $14<L_t<21$ml/s. Ranges of the third regime of liquid falling are $575 < \mathrm{Re} < 765$.

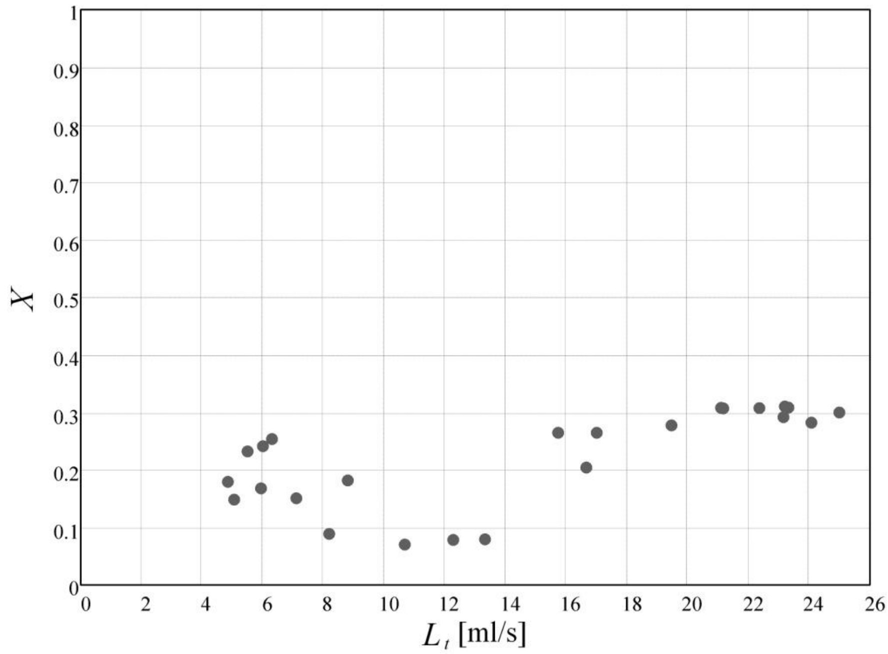

Figure 8. Dependence X on various L_t

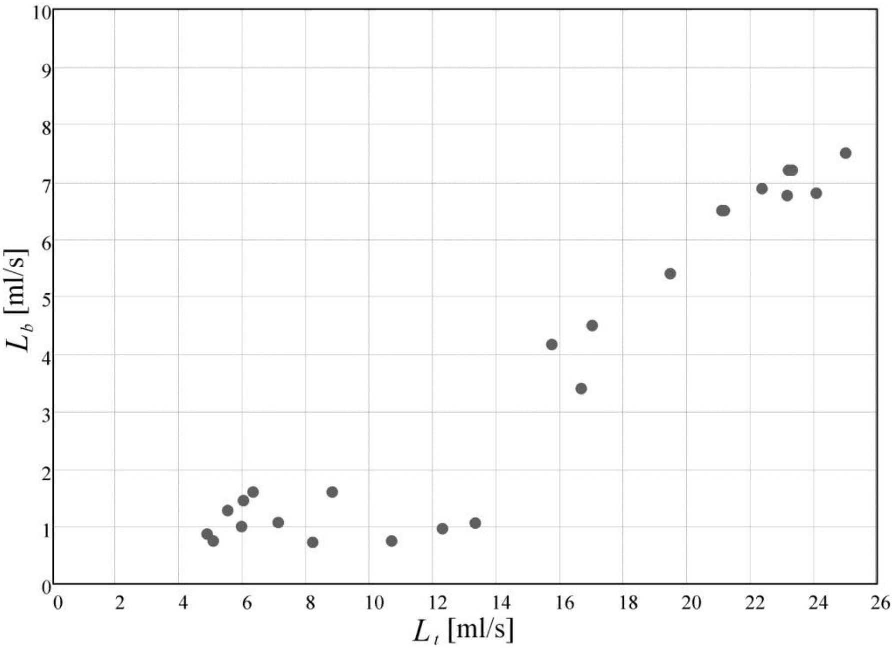

Figure 9. Dependence of L_b on various L_t

Authors suppose this regime is more rational than others for heat and mass transfer processes. The surface area of the falling fluid film on free surface in this regime is higher than in other regimes.

The fourth regime of the falling fluid film starts if the flow rate of irrigated liquid L_t is more than 21 ml/s (Re > 765). Falling liquid jets wash off and break “standing waves” on free surface of the fluid film (see Figure. 7d). The surface becomes flat on the front side of the packing element. The front side of the packing element sinks wholly in the fluid jet. Authors call this regime like “regime with flooding”. Authors watched that surface area of the falling fluid film in this regime is below than surface area of the fluid film in both sides flow regime with “standing waves”. Velocity of the liquid on free surface of the fluid film is more than velocity of the fluid in other regimes. This regime is not rational for heat and mass transfer processes on this structured packing because the surface area of the falling fluid film in this regime is below than the surface area of the falling film in other regimes. Increasing of dimensionless quantity *X* stops in this regime.

It is known [4] if fluid film is falling on the surface of the packing, minimum flow rate of the liquid have a hysteresis. There are two value of the minimum flow rate of the liquid. Minimum flow rate of the liquid is minimum value of the specific flow rate of the liquid on the width of the fluid film (kg/m·s or m^3/m·s) when the whole surface of the packing is wetted. The value of contact angle of the liquid irrigating the solid surface of the packing is the reason of two value of the minimum flow rate of liquid. The contact angle of the liquid has two values: liquid can flow on a dry surface or an already wet surface. The contact angle of the liquid will be high if it flows on a dry, solid surface of the packing. The contact angle of the liquid will be low if it flows on a wetted solid surface of the packing. The difference between two values of the minimum flow rate of liquid reaches to 1200% [4]. That’s why intensive pre-wetting of both sides of the packing elements is one of the ways to expand the range of optimum flow rates for this structured packing. Authors made another series of experiments. This series of experiments started at maximum flow rate of the liquid (about 23 ml/s). Then the flow rate of the liquid decreased until minimum (about 4 ml/s). The back side of the packing's element was irrigated intensive before the first measurement in every series of the experiments. For this purpose the liquid irrigated the back side of the packing element at the beginning of every series of measuring

As a result of experiments, the authors discovered that dimensionless quantity *X* increased from 0.3 to 0.5 after intensive irrigation of the back side of the packing element (see Figure. 10). The authors suppose that after intensive irrigating of the back side of the packing element, the liquid from the back side of the packing element engulfs the fluid film from the front side of the packing element through the slits. The authors suppose that after irrigation of the back side of the packing element, the liquid starts to flow to the back side of the packing element through the slits under the fluid film.

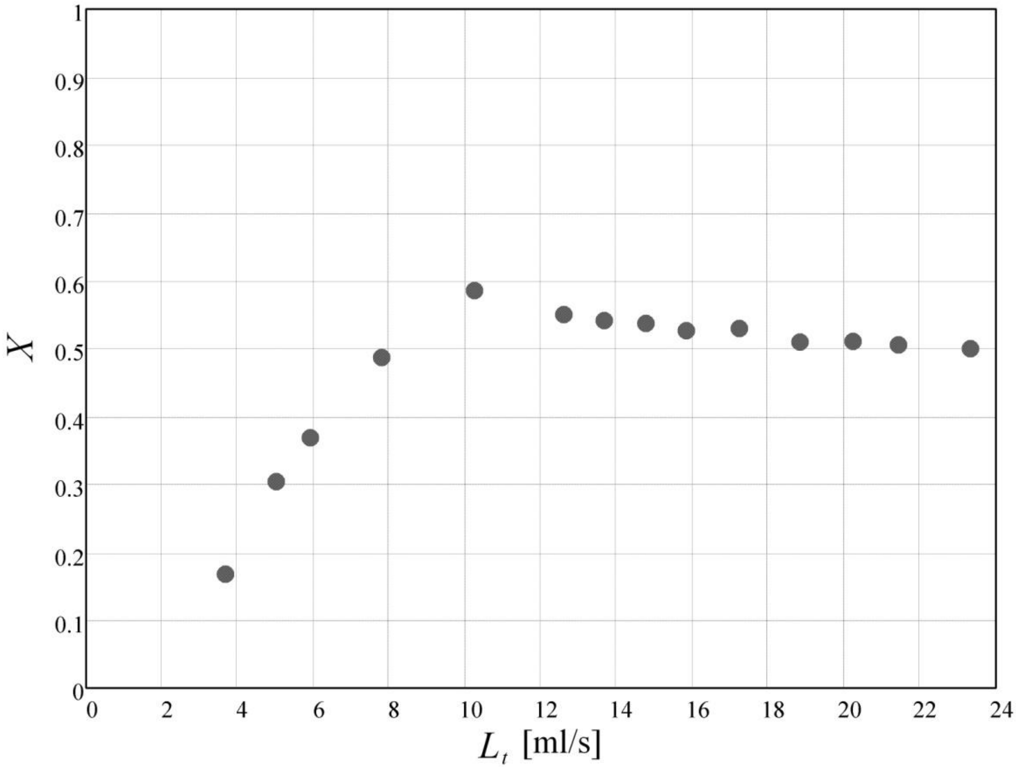

Figure 10. *Dependence X on various L_t*

Minimum value of the flow rate for the four regime of the fluid film falling (flow regime with flooding) is increased as a result of increasing of the dimensionless quantity *X* after intensive irrigation of the back side. Reducing of the flow rate on the front side of the packing element is the reason of this. Maximum flow rate for the third regime of flowing (both sides flow regime with "standing waves") is increased. Thus it is possible to increase the upper bound of the third regime of the fluid film falling.

If the flow rate of the liquid Lt continues to decrease to 10 ml/s, the dimensionless quantity *X* is increased slightly. According to the graph (Figure. 10), the part of the liquid entered through the slits from the front side of the packing element to the back side, is increased by 8%. For engineering calculations, authors propose to consider that half of the liquid flowed through the slits in the range of the liquid's flow rates of 10 to 25 ml/s. The film thickness is decreased with decreasing of the flow rate of the liquid from the 25 ml/s to 10 ml/s. In the first part of experiments (when the flow rate was growing up), the film thickness of the liquid remains approximately constant (especially if L_t<15 ml/s), but the width of the film is increased with increasing the flow rate.

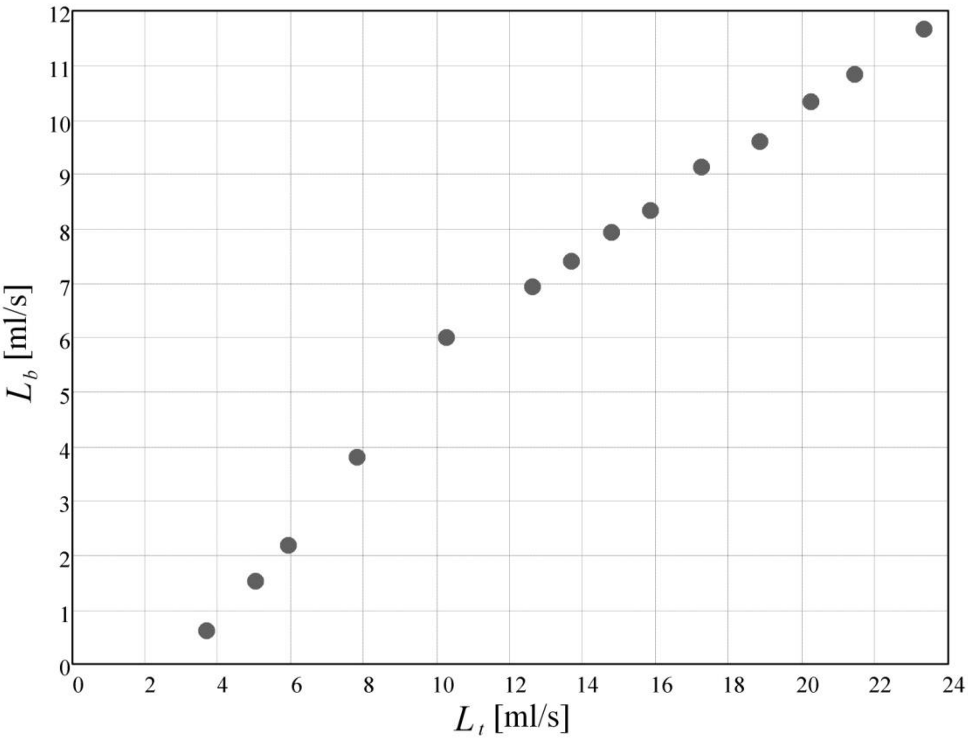

Figure 11. *Dependence L_b on various L_t*

Dimensionless quantity X decreases abruptly when the flow rate of the liquid decreases below 10 ml/s. The angle of the line on the Figure. 10 increases abruptly. Moreover, the authors observed abruptly decrease of the width of the fluid film. Wide liquid film was torn and transformed in the narrow jet (if $L_t < 10$ ml/s). As a result of reduced width of the fluid film, a number of slits that are passed the liquid to the back side of the packing element decreases. This is the reason for decreasing the part of the liquid X entered through the slits from the front side of the packing element on the back side of the packing element when the flow rate of the liquid is below 10 ml/s.

The authors propose to flood the packed bed to obtain pre-wetting of the both sides of the packing element in the wet scrubbers. This can be achieved in countercurrent scrubbers with proposed structured packing below loading line. The packed bed should be flooded before starting a process in the scrubber (or sometimes during the operation of the scrubber). For this, we need to increase the flow rate of the liquid L_t briefly. After that, we need to decrease the flow rate below loading line. The scrubber can be equipped with the addition spray nozzle for intermittent flooding during the operation of the wet scrubber.

5. CONCLUSIONS

The method of evaluation of the efficiency of the structured packings and quality of liquid's distribution on the surface using dimensionless quantity X is proposed. Rational flow rate for the new packing corresponds to Reynolds numbers from 575 to 765. Wherein 30% of the liquid flow to the opposite side of the new packing element in this range of the flow rate. The authors discovered by experiment, the part of the liquid X passed through the slits from the front side of the packing element on the back side of the packing element can be increased by pre-wetting the back side of the packing element. The authors propose to flood the packing in scrubbers before starting a process of heat and mass transfer in scrubber.

SYMBOLS

a geometric surface area per unit volume, m^2/m^3
b width of the fluid film, m
g acceleration due to gravity, m/s^2
L flow rate of the liquid, m^3/s
p pressure, Pa
q volumetric flow rate per width of fluid film, $m^3/m{\cdot}s$
w velocity of a fluid film, m/s
x *X* coordinate
y *Y* coordinate
z *Z* coordinate
Re Reynolds number of the fluid film
X part of the liquid entered through the slits from the front side of the packing element on the back side of the packing element (number of outflow)

Greek symbols

δ thickness of a fluid film, m
μ dynamic viscosity of a fluid, m^2/s
υ kinematic viscosity of a fluid, m^2/s
ρ density of a fluid, kg/m^3

Subscripts

2-3 maximum value for the second regime of the fluid film falling
fr collected from the front side of the packing element
b collected from the back side of the packing element
p on the peak of corrugation
t total
v on the valley of corrugation
x along *X* coordinate
y along *Y* coordinate
z along *Z* coordinate

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