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LIQUID HOLD-UP AND INTERFACIAL AREA IN HIGH-VELOCITY INJECTION SCRUBBERS

Common knowledge on interfacial area in high-velocity scrubbers is characterized. Its incompleteness and ambiguity are pointed out. A new mathematical model of the liquid hold-up and interfacial area in injection scrubbers is put forward, taking into account specific structure and dynamics of developing annular-dispersed flow. Some exemplary simulation results of the liquid hold-up and interfacial area are presented. The phenomenon of large interfacial areas developing in the liquid injection zone is explained.

NOMENCLATURE

A – cross-section area of the apparatus (m^2),
C – mass concentration of the liquid phase (kg/m^3),
d_K, $\bar{d}_K$ – droplet diameter, mean droplet diameter (m),
D_A – scrubber throat diameter (m),
F – interfacial area (m^2),
g – acceleration due to gravity (m/s^2),
m_K – single droplet mass (kg),
$\dot{M}$ – mass flow rate (kg/s),
n – number of the apparatus cross-section examined,
$Nz = \dot{V}_c/\dot{V}_g$ – liquid to gas flow rate ratio (m^3/m^3),
t – time (s),
V – volume of the phase examined (m^3),
$\dot{V}$ – flow rate (m^3/s),
w, $\bar{w}$ – velocity, mean velocity (m/s),
x – distance from the liquid injection section (m),
Z – liquid hold-up (m^3/m^3).

GREEK SYMBOLS

δ_F – film thickness (m),
Δ – difference, increase,
χ – factor taking into account influence of film ripple on the value of interfacial area,

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η – viscosity (kg/(m · s)),
ρ – density (kg/m^3),
τ – quantity in equation (6) (according to [29]) (kg/s),
τ_i – interfacial shear stress (N/m^2),
ϕ – quantity in equations (7) and (8) (according to [29]).

SUBSCRIPTS

A – apparatus,
c – liquid phase or position in the throat axis,
F – film,
g – gas phase,
K – droplets,
o – initial conditions.

1. INTRODUCTION

Injection scrubbers are classified among the Venturi scrubbers. All scrubbers of this type have one common characteristics, namely that working liquid injection, its disintegration into droplets and transport along contact zone take place due to the

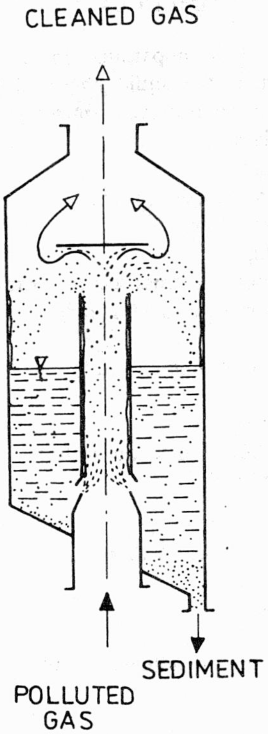

Fig. 1. Operating principles of injection scrubbers

energy of the gas being cleaned (figure 1). A conspicuous advantage of these apparatuses is circulation of liquid without pumps and jets, which makes them unfailing and convenient in utilization. Determination of the interfacial area value and liquid hold-up in the working zone have fundamental significance for evaluation of heat and mass transfer processes in injection scrubbers.

Scientific reports on interfacial area in the Venturi scrubbers are more than scarce and ambiguous. Some research results [1]–[6] are presented in the form of the products of mass transfer coefficients and the interfacial areas or unitary interfacial areas. Such data is not much useful in designing the cleaning processes. Because of a considerably varied manner of defining the mass transfer coefficients and unitary interfacial areas, the results presented in those papers are difficult to compare, and the final evaluation of their usefulness is practically impossible.

Another group of publications presents results in the form of absolute interfacial areas [7]–[10]. The results are difficult to compare as they are directly connected with the apparatus geometry. The measured interfacial areas were changing within a wide range, from 0.1 m^2 [7] to 350 m^2 [8].

It seems that for comparison purpose, the most advantageous form of interfacial area presentation is unitary area referred to the apparatus volume. Research results expressed in this form are presented in papers [11]–[20].

In table 1, for comparison, ranges of unitary interfacial areas reported by various authors have been compiled.

Table

Values of interfacial areas related to the apparatus volume, quoted in publications

Authors of the publication	Literature position	Type of flow or apparatus	Range of interfacial area, m^2/m^3
KASTURI and STEPANEK	[16]	Two-phase flow directed vertically from the bottom upwards	400–1000
WALES	[17]	Horizontal annular -dispersed flow	400–2200
NAGEL et al.	[15]	Jet pumps, Venturi scrubbers	110–1400 1100–10000
RADHAKRISHNAN and MITRA	[14]	Vertical dispersed flow directed from the bottom upwards	450–2650
SHILIMKAN and STEPANEK	[13]	Vertical annular-dispersed flow directed from the bottom upwards	200–500

MAYINGER and NEUMAN [11] presented in the graphic form the characteristics of unitary interfacial area variation in Venturi scrubber at a high gas velocity in the throat, amounting to 80 m/s, and liquid to gas flow rate ratio equal to $2.46 \cdot 10^{-3}$ m^3/m^3. From this characteristics it is evident that local unitary interfacial areas can reach very high values, even of the order of 10^5 m^2/m^3, though, obviously, mean area referred to the overall scrubber volume is usually two orders lower.

RADHAKRISHNAN and MITRA [14] discovered that local unitary interfacial area in the liqiud disintegration zone reached the value of 25000 m^2/m^3, and for the whole system it ranged from 450 to 2650 m^2/m^3.

To sum up: so far there has been no perspicacious model of interfacial area in injection scrubbers. Such a model should enable one to calculate local values of liquid hold-up and interfacial area, separately for droplets and film. It should also take into accuont hydrodynamic conditions of operation and geometry of apparatus.

2. MODELLING OF INTERFACIAL AREA IN THE SCRUBBER THROAT

Modelling of interfacial area development process in injection scrubbers calls for exact calculation of local liquid hold-up values, and especially of liquid appearing in the form of droplets. Hold-up of droplets in a part of the scrubber throat between sections n and $n+1$ amounts to

$$Z_K(n; n+1) = \frac{V_K(n; n+1)}{V_A(n; n+1)}, \tag{1}$$

and of the film

$$Z_F(n; n+1) = \frac{V_F(n; n+1)}{V_A(n; n+1)}. \tag{2}$$

It can be written that

$$V_K(n; n+1) \approx \dot{V}_K(n)\Delta t \tag{3}$$

and

$$V_F(n; n+1) \approx \dot{V}_F(n)\Delta t_F(n; n+1). \tag{4}$$

Moreover, taking into account that the time of film movement between sections n and $n+1$ is

$$\Delta t_F(n; n+1) = \frac{x(n+1) - x(n)}{\bar{w}_F(n)} \tag{5}$$

and that $\Delta x = x(n+1) - x(n)$ can be calculated by means of eqn. (6) ([29])

$$x = \left(w_g - \frac{m_K}{\tau}\right)t + \left(\frac{m_K}{\tau}\right)^2 \cdot \left\{[w_g - (w_K)_o] \cdot \frac{\tau}{m_K} - g\right\}[e^{-\frac{\tau}{m_K}t} - 1], \tag{6}$$

whereas $\bar{w}_F(n)$ by making use of eqns. (7)–(9) ([29])

$$\bar{w}_F = \frac{\delta_F}{\eta_c}\left(\frac{\rho_c \phi g}{3}\delta_F - \frac{\tau_i}{2}\right), \tag{7}$$

$$w_{Fi} = w_F(\delta_F) = \frac{\rho_c \phi g \delta_F}{\eta_c}\left[-\frac{\tau_i}{\rho_c \phi g} + \frac{\delta_F}{2}\right], \tag{8}$$

$$\dot{V}_F = \bar{w}_F A_F = \bar{w}_F\left[\frac{\pi D_A^2}{4} - \frac{\pi}{4}\left(D_A - 2\delta_F\right)^2\right], \tag{9}$$

a series of simulation experiments has been carried out in order to investigate variation of local liquid hold-up in the form of droplets and film. Exemplary simulation results are presented in figure 2.

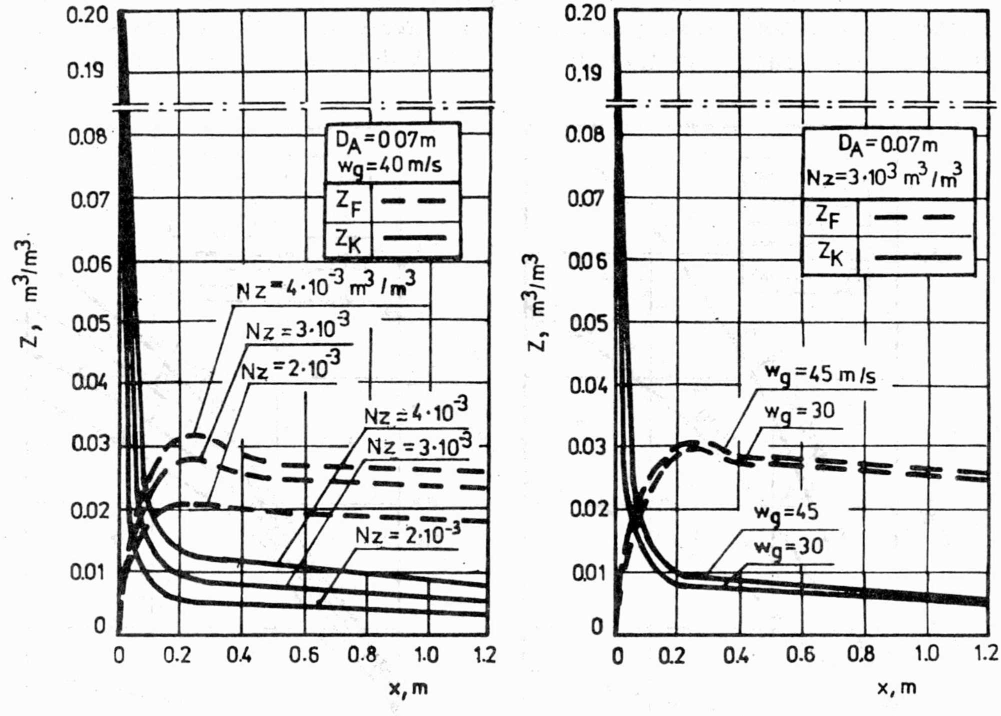

Fig. 2. Exemplary simulation results for local hold-up values of liquid droplets and film

Absolute local interfacial area in each of the examined parts of the throat consists of the area developed by droplets and film

$$F(n;\, n+1) = F_K(n;\, n+1) + F_F(n;\, n+1), \tag{10}$$

where

$$F_K(n;\, n+1) = \frac{6\, V_K(n;\, n+1)}{\bar{d}_K(n)} \tag{11}$$

and

$$F_F(n;\, n+1) = \pi[D_A - 2\,\delta_F(n)] \cdot [x(n+1) - x(n)]\,\chi(n). \tag{12}$$

The value of $\chi(n) \geq 1$ allows us to include a growing influence of film ripple on interfacial area.

At the present stage of knowledge on the subject, it is not possible to evaluate precisely local values of the factor $\chi(n)$; however, on the basis of the papers by TAKAHAMA and others [21] as well as those by UEDA and TANAKA [22] on amplitude and frequency of film ripple in annular-dispersed flows, it can be estimated that the values of the amplitudes range within 0.25–1.5 δ_F, and the frequencies within 20–100 Hz. In these conditions (taking into consideration velocity of wave movement), the factor χ, taking account of an increase of interfacial area as a result of its ripple, can range from 1.00005 to 1.0032. Validity of such an estimation has

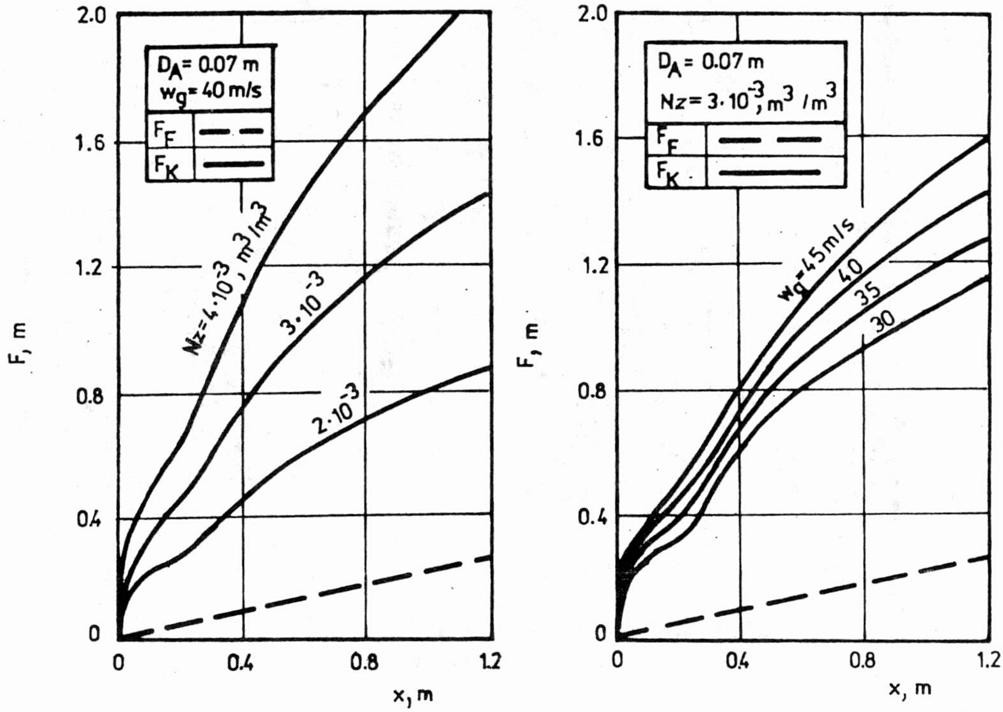

Fig. 3. Exemplary simulation results for the absolute interface area

also been confirmed by the authors of the latest papers [23]–[25] on the film structure in annular-dispersed flows. Additionally, bearing in mind that $\delta_F \ll D_A$, it becomes obvious that exclusively interfacial area developed by film depends practically on the diameter and length of the scrubber throat. Thus interfacial area developed by film in that part of the apparatus between sections n and $n+1$ can be considered as cylindrical surface and expressed by a simplified dependence

$$F_F(n;\, n+1) \approx \pi D_A[x(n+1) - x(n)] \tag{13}$$

and the modelling of liquid hold-up in the form of film becomes a by-issue.

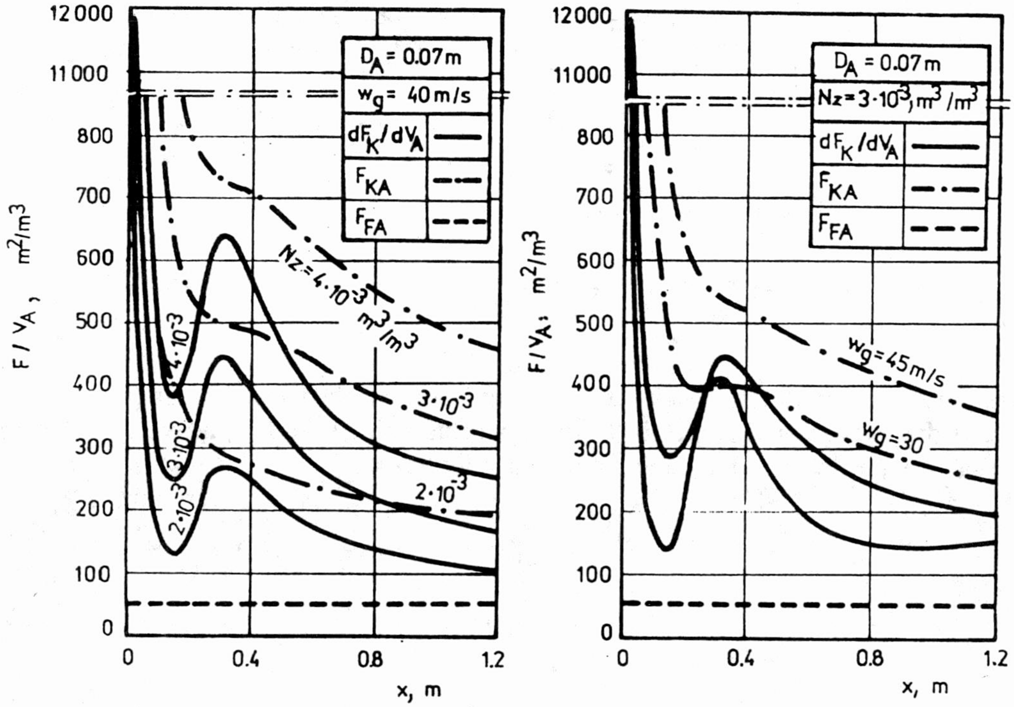

Fig. 4. Exemplary simulation results for the unitary interface area related to the scrubber volume

A result of hold-up of droplets and interfacial area developed by them, however, should be approached in a totally different manner, as the local values of these parameters change within very wide limits.

On the basis of the mathematical model of axial movement of droplets presented in paper [29] and taking into consideration eqns (3), (11) and (13), the simulation of variation in interfacial area developed by droplets and film was carried out. Exemplary results of such experiments are shown in figure 3. In figures 4 and 5, there

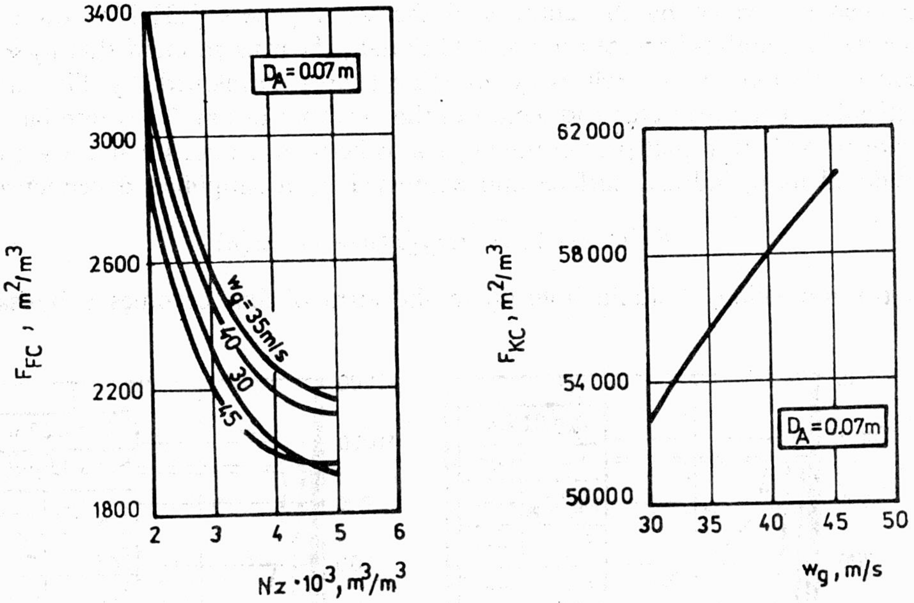

Fig. 5. Exemplary simulation results for the unitary interface area related to the liquid volume
a – for the film, b – for the droplets

are presented simulation results of variation in unitary interfacial areas for film and liquid droplets related respectively to apparatus volume and liquid volume. These areas can be described by the following equations:

$$F_{KA}(n; n+1) = \frac{24\dot{V}_K(n)\Delta t}{\pi D_A^2[x(n+1) - x(n)]\bar{d}_K(n)}, \tag{14}$$

$$F_{FA}(n; n+1) \approx \frac{4}{D_A}, \tag{15}$$

$$F_{Kc}(n; n+1) \approx \frac{6}{\bar{d}_K(n)}, \tag{16}$$

$$F_{Fc}(n; n+1) = \frac{\pi D_A[x(n+1) - x(n)]}{\dot{V}_F\Delta t}. \tag{17}$$

3. AN EXPLANATION OF LARGE INTERFACIAL AREA PHENOMENON IN LIQUID INJECTION ZONE

Analysing the results of simulation experiments one could make an attempt at explaining a phenomenon of very large absolute and unitary interfacial areas developing in a relatively small part of the throat, directly behind the liquid injection

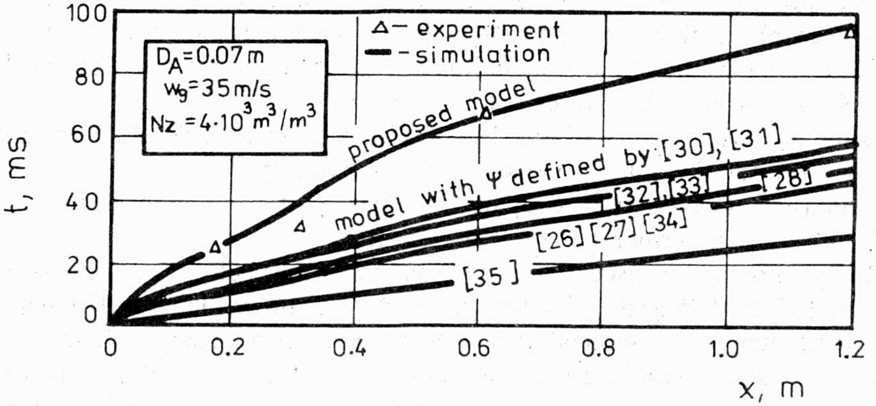

Fig. 6. A comparison of the physical experiment results with the droplet movement simulation results obtained from different formulas describing the drag coefficient

section. In order to do that, it is necessary to quote the simulation results of axial movement of droplets in that zone presented in figure 6 and published in paper [29]. It is not difficult to notice that the acceleration of droplets near the injection section is much lower than it might result from calculations taking account of the drag coefficient recommended, e.g. by HESKETH [26], AZZOPARDI [27] or BAYVEL [28]. Bearing in mind the principle of movement continuity for dispersed phase that can be expressed as

$$\dot{M}_K = C_K(n)\cdot w_K(n)\cdot A = C_K(n+1)\cdot w_K(n+1)\cdot A = \text{const}, \tag{18}$$

it can be written that

$$C_K \sim \frac{1}{w_K} \tag{19}$$

and

$$Z_K \sim \frac{1}{w_K}. \tag{20}$$

Thus small axial velocities of droplets are accompanied by their high concentration in the gas core and high values of liquid hold-up.

A detailed analysis of characteristic division of the liquid stream into droplets and film [29] demonstrated that in the initial part of the throat, right behind the liquid injection section, fraction of droplets in the total liquid stream is very high, but as a result of intensive droplet deposition on the walls the fraction quickly decreases and at the distance as short as 2–3 D_A from the liquid injection section it reaches a minimal value. It reduces decidedly local interfacial area values.

Therefore it can be declared that in the case of injection scrubbers (also in other Venturi scrubbers) there are some objective causes for development of much larger interfacial areas in the initial zone (adjoining the injection section) than in the other parts of the throat. The causes are as follows:

– small initial velocities of droplets, implying their large local concentrations in the gas core and high local values of liquid hold-up,

– intensive deposition of droplets on the throat walls, considerably reducing interfacial area in farther parts of apparatus.

The phenomenon discussed here was perceived before by MATROZOV and FILATOV [7] in 1975 and by MAYINGER and NEUMANN [11] in 1979, who carried out measurements of interfacial area in Venturi scrubbers using a chemical method. Both Soviet and German researches, not being able to investigate in detail the mechanisms of interfacial area development (the investigative method applied had rendered it impossible), tried to explain the occurrence of so large interfacial areas in the liquid injection zone by suggestion that the cause is to be found in the very process of liquid disintegration. Meanwhile, the results of physical experiments presented in paper [29], the mathematical model set forth above as well as the simulation research allow us to draw a conclusion that the reached values of interfacial area are related to specific dynamics of the developing annular-dispersed flow.

REFERENCES

[1] VOLGIN B.P., NORKINA L.A., JUGAJ F.S., *Sravnenie forsunochnogo i besforsunochnogo absorberov Venturi*, Processy i Apparaty Khimicheskoi Technologii, 855, pp. 55–60, 1971.

[2] NORKINA L.A., VOLGIN B.P., JUGAJ F.S., *Zakonomernost izmereniya koefficienta massoperedachi v zavisimosti ot konstanty fazovo ravnovesiya v absorbere Venturi*, Zhurnal Prikladnoi Khimii, 12, pp. 2703–2706, 1980.

[3] NORKINA L.A., VOLGIN B.P., *O soprotivlenii faz massoperedachi pri absorbcii khorosho rastvorimogo gaza w skrubbere Venturi*, Zhurnal Prikladnoi Khimii, 1, pp. 94–99, 1971.

[4] DELHAJ S., GUERIN P., LIMNIOS N., ZOULALIAN A., *Analyse Energetique de l'Efficacite d'un Absorbeur Reactionnel du Type Venturi a Jet*, Chem. Eng. J., 26, pp. 21–32, 1983.

[5] TOMIDA T., YOSHIDA M., OKAZAKI T., *Liquid-Side Volumetric Mass Transfer Coefficient in Upward Two-Phase Flow of Air–Liquid Mixtures*, J. Chem. Eng. Japan, 9, 6, pp. 464–468, 1976.

[6] SHILIMKAN R.V., STEPANEK J.B., *Effect of Tube Size on Liquid Side Mass Transfer in Co-Current Gas–Liquid Upward Flow*, Chem. Eng. Sci., 12, 11, pp. 1397–1400, 1977.

[7] MATROZOV V.J., FILATOV N.N., *Massoobmen v absorbere Venturi v zone dispergirovaniya zhidkostnogo potoka*, Zhurnal Prikladnoi Khimii, 1, pp. 103–108, 1975.

[8] NAGEL O., KÜRTEN H., SINN R., *Strahldüsenreaktoren*, Chemie-Ing. Techn., 42, 7, pp. 474–479, 1970.

[9] NAGEL O., KÜRTEN H., SINN R., *Stoffaustauschfläche und Energiedissipationsdichte als Auswahlkriterien für Gas/Flüssigkeits-Reaktoren*, Ing. Techn., 44, 6, pp. 367–373, 1972.

[10] LAURENT A., FONTEIX C., CHARPENTIER J.C., *Simulation of a Pilot Scale, Motivated, Venturi Jet Scrubber by a Laboratory Scale Model*, AIChE Journal, 26, 2, pp. 282–287, 1985.

[11] MAYINGER F., NEUMANN M., *Neue Gleichung zur Berechnung der Staubabscheidung im Hochleistungs-Venturiwäscher*, VDI-Berichte, 349, pp. 309–320, 1979.

[12] MUNTER R.R., LOORITS Ch.A., SIJRDE E.K., *Sravnitelnaya ocenka razlichnykh massoobmennykh apparatov po velichine aktivnoi poverkhnosti kontakta*, Zhurnal Prikladnoi Khimii, 10, pp. 2336–2338, 1979.

[13] SHILMKAN R.V., STEPANEK J.B., *Interfacial Area in Cocurrent Gas–Liquid Upward Flow in Tubes of Various Size*, Chem. Eng. Sci., 32, pp. 149–154, 1977.

[14] RADHAKRISHNAN V.R., MITRA A.K., *Pressure Drop, Holdup and Interfacial Area in Vertical Two-Phase Flow of Multi-Jet Ejector Induced Dispersions*, Can. J. Chem. Eng., 62, 2, pp. 170–178, 1984.

[15] NAGEL O., KÜRTEN H., SINN R., *Stoffaustauschfläche und Energiedissipationsdichte als Auswahlkriterien für Gas/Flüssigkeits-Reaktoren*, Chemie-Ing. Techn., 44, 14, pp. 899–903, 1972.

[16] KASTURI G., STEPANEK J.B., *Interfacial Area in Cocurrent Gas–Liquid Flow*, Chem. Eng. Sci., 29, pp. 713–719, 1974.

[17] WALES Ch.E., *Physical and Chemical Absorption in Two-Phase Annular and Dispersed Horizontal Flow*, AIChE Journal, 12, 6, pp. 1167–1176, 1966.

[18] STRAVS A.A., von STOCKAR U., *Measurement of Interfacial Areas in Gas Liquid Dispersions*, Chem. Eng. Sci., 7, pp. 1169–1175, 1985.

[19] MERSMANN A., HOFER H., STICHLMAIR J., *Absorption und Absorber*, VDI-Berichte, 349, pp. 59–68, 1979.

[20] ULRICH M., *Der Strahlapparat als Wäscher und Reaktor*, Verfahrenstechnik, 14, 12, pp. 831–835, 1980.

[21] TAKAHAMA H., OKADA O., FUJITA H., MIZUNO A., *Study on Annular Mist Flow in Pipe*, Bull. ME, 26, 222, pp. 2091–2099, 1983.

[22] UEDA T., TANAKA T., *Studies of Liquid Film Flow in Two-Phase Annular and Annular-Mist Flow Regions*, Bull. JSME, 17, 107, pp. 603–613, 1974.

[23] GOVAN A.H., HEWITT G.F., OWEN D.G., BURNETT G., *Wall Shear Stress Measurements in Vertical Air–Water Annular Two-Phase Flow*, Int. J. Multiphase Flow, 15, 3, pp. 307–325, 1989.

[24] WASDEN F.K., DUKLER A.E., *Numerical Investigation of Large Wave Interactions on Free Falling Films*, Int. J. Multiphase Flow, 15, 3, pp. 357–370, 1989.

[25] SAWAI T., YAMAUCHI S., NAKANISHI S., *Behaviour of Disturbance Waves Under Hydrodynamic Non-Equilibrium Conditions*, Int. J. Multiphase Flow, 15, 3, pp. 341–356, 1989.

[26] HESKETH H.E., MOHAN K., *Specifying Venturi Scrubber Throath Length for Effective Particle Capture at Minimum Pressure Loss Penalty*, JAPCA, 33, 9, pp. 854–857, 1983.

[27] AZZOPARDI B.J., GOVAN A.H., *The Modeling of Venturi Scrubbers*, Filtr. Separ., 3, pp. 196–200, 1984.

[28] BAYVEL L.P., *The Effect of the Polydispersity of Drops on the Efficiency of a Venturi Scrubber*, Trans. Inst. Chem. Eng., 60, 1, pp. 31–34, 1982.

[29] MELOCH H., *Injection scrubbers for waste gases cleaning – background of operation*, Scientific Papers of the Institute of Environmental Protection Engineering of the Technical University of Wrocław, No. 66, Monographs No. 34, 1991.

[30] CALVERT S., LUNDGREN D., MEHTA D.S., *Venturi Scrubber Performance*, JAPCA, 22, 7, pp. 529–536, 1972.

[31] GOEL K.C., HOLLANDS K.G.T., *A General Method for Predicting Particulate Collection Efficiency of Venturi Scrubbers*, Ind. Eng. Chem. Fundam., 16, 2, pp. 186–193, 1977.

[32] BEHIE S.W., BEECKMANS J.M., *On the Efficiency of a Venturi Scrubber*, Can. J. Chem. Eng., 51, pp. 430–433, 1973.

[33] COONEY D.O., *Modeling Venturi Scrubber Performance for Oil-Shale Retort Gases*, Chem. Eng. Commun., 35, pp. 315–338, 1985.

[34] VAL'DBERG A.J., CHUTOROV J.F., *Tiporazmernyi ryad vysokotemperaturnykh skrubberov Venturi*, Prom. Sanit. Ochistka Gazov, 2, pp. 2–3, 1985.

[35] PALATNIK J.B., *Osnovy rabochego processa pyleulavlivaniya pri ispolzovanii trub-koagulatorov Venturi*, Alma-Ata, Izdatelstvo Nauka Kazakhskoi SSR, 1977.

ZATRZYMANIE CIECZY I POWIERZCHNIA KONTAKTU FAZ W WYSOKOPRĘDKOŚCIOWYCH PŁUCZKACH INIEKCYJNYCH

Scharakteryzowano dostępne dane o powierzchni kontaktu faz w wysokoprędkościowych płuczkach. Wskazano na ich fragmentaryczność i niejednoznaczność. Zaproponowano nowy model matematyczny zatrzymania cieczy i powierzchni kontaktu faz w iniekcyjnych płuczkach, uwzględniający specyficzną strukturę i dynamikę rozwijającego się przepływu pierścieniowo-dyspersyjnego. Przedstawiono przykładowe rezultaty symulacji zatrzymania cieczy i powierzchni międzyfazowej. Wyjaśniono fenomen rozwijania dużych powierzchni międzyfazowych w strefie iniekcji cieczy.

ЗАДЕРЖИВАНИЕ ЖИДКОСТИ И ПОВЕРХНОСТЬ КОНТАКТА ФАЗ В ВЫСОКОСКОРОСТНЫХ ИНЪЕКЦИОННЫХ РАСТВОРАХ

Охарактеризованы доступные данные на тему поверхности контакта фаз в высокоскоростных растворах. Указана их фрагментарность и неоднозначность. Предложена новая математическая модель задерживания жидкости и поверхности контакта фаз в инъекционных растворах, учитывающая специфическую структуру и динамику развивающегося циклично-дисперсионного течения. Представлены примерные результаты имитации задерживания жидкости и межфазовой поверхности. Выяснен феномен развития больших межфазовых поверхностей в зоне инъекции жидкости.