HYDRODYNAMICS AND MASS TRANSFER OF A TWO-PHASE COUETTE-TAYLOR FLOW REACTOR

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Helicoidal flow in an annular gap in an apparatus with a rotating internal surface is a superposition of two simple flows: axial Poiseuille flow and rotating Couette flow (Couette-Taylor-Flow/CTF). Due to cell eddies occurring in the CTF reactor this a rare type of flow combining intense local mixing with a limited axial dispersion. This is a very advantageous feature of the CTF reactor [1]. Recently, the above mentioned properties of the helicoidal flow have resulted in a significantly increased interest in that type of reactors.

In our paper [2, 3,4] an application of the helicoidal flow in the membrane reactors has been suggested. In such an apparatus gas is fed into the reaction space through a stationary cylindrical hydrophobic membrane equipped with a rotating cylinder immersed inside it. A fluid flows along an axial cylindrical gap. After crossing over the critical bubbling pressure a two-phase gas-liquid flow is obtained. Because of the flow condition in the gap the gas bubbles are vigorously mixed. Intensity control of the local fluid mixing makes it possible to influence the course of the complex reactions, e.g. slectivity control, by changing the rotation speed of the rotor. Experiments indicate high values of the mass transfer coefficients (k_La = $1\div10^{-1}$ s^{-1}), (Fig. 1) in the high viscosity liquids, too [2, 3].

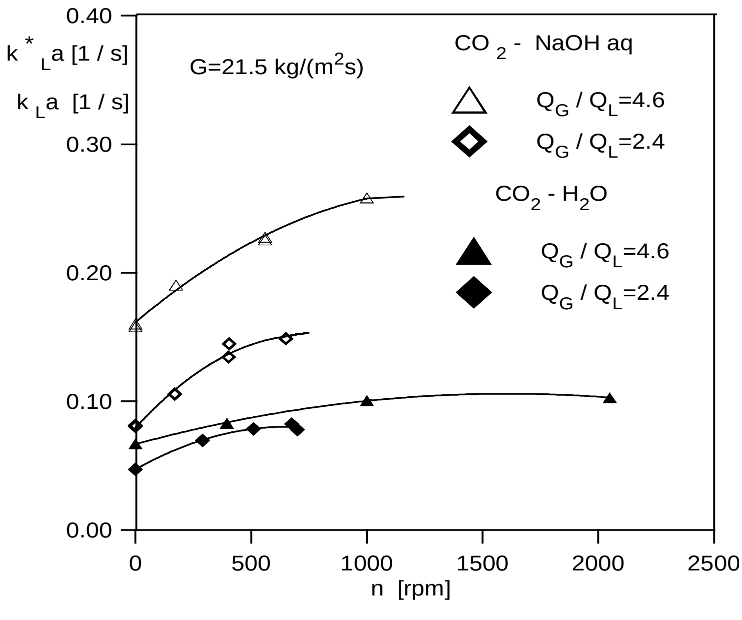


Fig.1. Comparison of the mass transfer coefficients measured for the physical absorption of CO_2 in water and those obtained for chemically enhanced absorption in an aqueous solution of NaOH. Q_G,Q_L- volumetric gas and liquid flow rate [dm^3/s]

If there is a need for a continuous gas introduction along the membrane because of necessity to maintain a high concentration of the substrate at the entire reactor surface or requirements on the process selectivity, a zone feeding at the limited reactor surface can be considered. In the limiting case, i.e. feeding the reactor with a gaseous substrate in the entrance zone, the reactor operates as a gap helicoidal reactor.

A comparison of the effectiveness of such a reactor with those of other type, requires determination of the power demand in the helicoidal reactor. A number of papers are available which enable to estimate the rotational moments of the rotor in a Couette flow. However, there is no information on interaction of the axial flow on the power demand, as well as on the fundamental data of the two-phase flow in CTF.

An investigation of hydrodynamics of the gap reactor has been carried out in an equipment where the measurements of the rotational moments of the rotor for a single and a two-phase flow and a visualization of the flow structures were possible, Fig.2. Three rotors of diameters (D_w) 40, 47 and 55 mm, and 450 mm long were used. The rotational speed of the shaft was changed from 300 to 2000 rpm. In order to attain a two-phase flow the systems nitrogen-water and nitrogen – an aqueous solution of an elevated viscosity were applied. In order to maintain the constant volumetric holdups of both phases along the entire length of the reactor, the two-phase flow was generated at the inlet cross section of the reactor. This allowed to simulate the conditions in the given cross section of a real membrane reactor with a continuous side feeding.

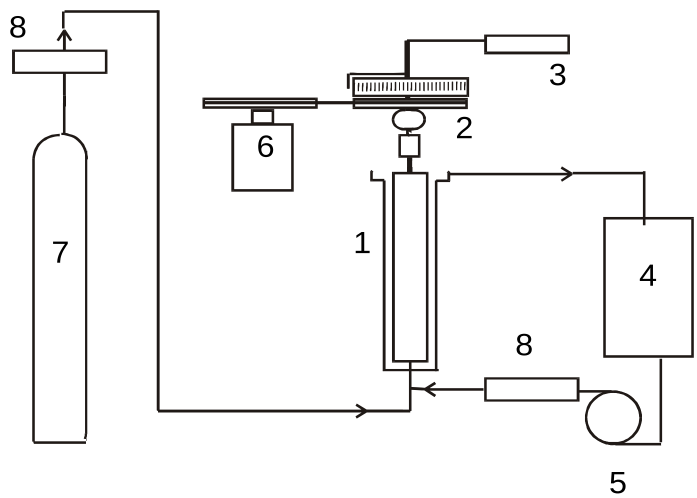
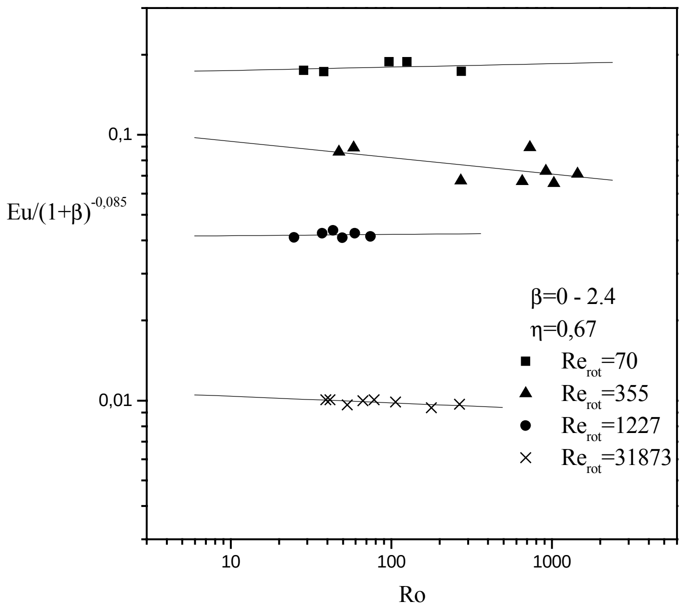


Fig. 2. Sketch of the experimental equipment:1-helicoidal reactor, 2,3 - torque and rotation speed measurement system, 4- liquid tank, 5-pump, 6- driving engine, 7-gas cylinder, 8 - flowmeters.

The measurements were conducted at different liquid flow rates (for a single fluid flow) and at different flow rates of a mixture with a variable gas holdup (for a two-phase flow). A relatively small influence of the axial flow and an effect of the gas holdup on the dissipated energy in the CTF have been found, Fig.3. The experimental results have been generalized and presented in a graphical form (for example Fig.4). There is also given the Wendt's correlation for simple one phase Couette flow, [5].



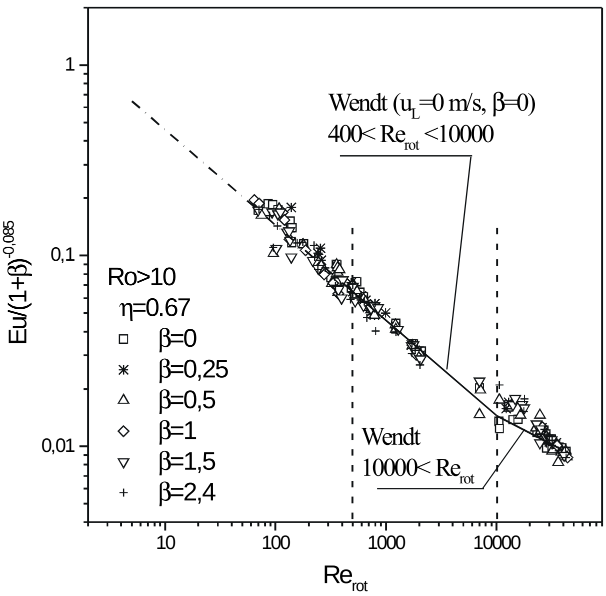


Fig.3 Dependence of modified Euler number on Rosby number

Fig.4. Dependence of modified Euler number on rotational Reynolds number

The visual observations have revealed an interesting structure of the two-phase flow. (with some range of the operational parameters). Distinct spiral Taylor vortices in the liquid phase have been observed as well as a thin region of the well-mixed gas between the vortices has been marked. These enables to suggest a model of the process based on a concept of a perfectly mixed cascade of the liquid reactors contacting with a vigorously stirred gas phase.
The helicoidal reactor, owing to its tubular construction is suitable to operate in a continuous process under an elevated pressure, e.g. to oxidize organic liquids.
In the Wet Air Oxidation-WAO method (one of the advanced oxidation method) two fundamental problems appear: how to intensify diffusional mass transfer and which catalysts should be used in order to increase the rate of chemical reactions. It should be pointed out that for the case of technical apparatus even where catalysts are applied, diffusional factors control the overall process rate. Under such circumstances the gap reactor could be applicable to aerate slurries and suspensions, even under the conditions corresponding to those encountered to the WAO process, in particular when contaminations present in the high viscosity liquids are to be removed and there is no demand for a high capacity equipment.
Owing to the potential perspectives of the reactor application in liquid oxidation, the model investigations using catalytic benzaldehyde oxidation by oxygen and air have been carried out. The obtained results have confirmed the possibility to achieve high values of the mass transfer coefficients under the conditions of a simultaneous chemical reaction present, also in suspensions of high viscosity. Mass transfer experiments have been performed in the systems: CO_2-water, air-benzaldehyde and oxygen-benzaldehyde at 293K, Fig.5. During the measurements of carbon dioxide absorption in water variant A (without the recirculation vessel), while in the case of benzaldehyde oxidation - variant B (with the recirculation vessel) have been used, respectively [4].

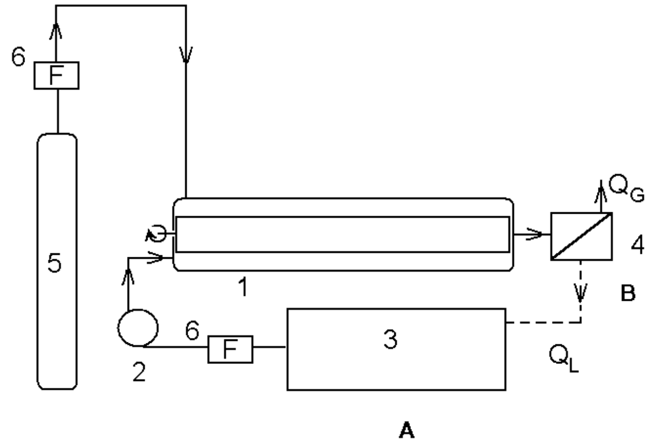


Fig. 5. Sketch of the experimental setup: (1) helicoidal reactor, (2) pump, (3) tank, (4) gas-liquid separator, (5) gas cylinder, (6) flowmeters.

The results have been generalized and presented in form of dimensionless number correlation (Fig.6).

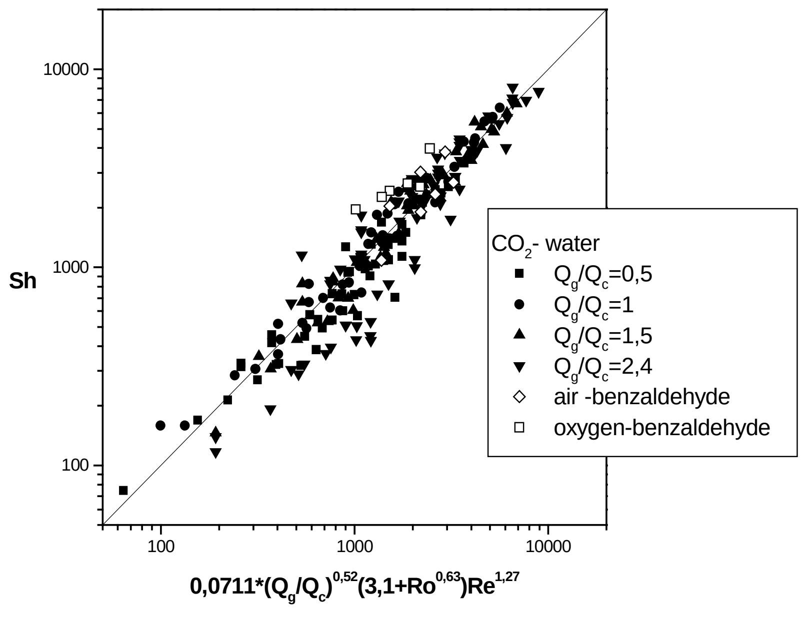


Fig.6. The mass transfer in two-phase (gas-liquid) Couette-Taylor Flow correlation

SUMMARY

a) The dependence of the values of the mass transfer coefficients in a two-phase helicoidal reactor on the energy dissipated in the rotational and axial flows has been presented. The obtained high values of these coefficients, of the order of 10^{-1} s^{-1} for the physical absorption and absorption with chemical reaction (oxidation of benzaldehyde).
b) This result gives rise to practical application of the tubular reactor in oxidation of organic liquids and suspensions at the normal and elevated pressures.

c) Large effect of the axial velocity on the values of the mass transfer coefficients has been found as compared with that of the rotational speed of the rotor.
d) The limiting values of the rotational speed have been established above which the effect of this parameter becomes insignificant.

NOTATION

a –interface area, m^{-1}
d - annular gap dimension of the reactor, m
D – diffusion coefficient, m^2/s

$$Eu = \frac{P}{\omega^3 \rho R_1^{3,5} L (R_2 d)^{0,25}}$$ - modified Euler number

P-power demand, W
ω-angular velocity of the inner cylinder
$k_L a$ – volumetric mass transfer coefficient, 1/s
$k^*_L a$ volumetric mass transfer coefficient with simultaneous chemical reactor, 1/s
n rotational speed, rpm
Q_G volumetric gas flow rate, Ndm^3/s
Q_L volumetric liquid flow rate, dm^3/s
u_L liquid velocity, m/s
u_G gas velocity, m/s
μ_{TP}, ρ_{TP} gas-liquid (TP=two phase) viscosity and density, Pa s
L – lenght of the reactor, m
R_1, R_2 –inner and outer cylinder radius, m

$$Re = \frac{u 2 d \rho}{\mu}$$ - Reynolds number

$$Re_{rot} = \frac{\omega\, d R_1 \rho_{TP}}{\mu_{TP}}$$ angular Reynolds number

$$Ro = \frac{\omega d_w}{2(u_L + u_G)}$$ Rossby number

$$Sh = \frac{k_L a d^2}{D}$$ -Sherwood number

$\eta = R_1/R_2$

REFERENCES

1. Desmet, G., Verelst, H., Baron, G., Desmet, G., Verelst, H., Baron, G., *Local and global dispersion effects in Couette-Taylor flow -II. Quantitative measurements and discussion of the reactor performance,* Chemical Engineering Science 51, 1299 – 1309, 1996.
2. Wroński, S., Dłuska, E., Hubacz, R., Molga, E., *Membrane helicoidal reactor*, Proceedings of the 2nd Conference „Membranes and Membrane Processes in Environmental Protection", Ustron-Jaszowiec, Poland, Oct. 23-25, Vol.1, 93-100, 1997.
3. Wroński, S., Dłuska, E., Hubacz, R., Molga, E., *Mass transfer in gas-liquid Couette-Taylor flow in membrane reactor,* Chem. Eng. Sci., 54, 2963-2967,1999.
4. Dłuska, E., Wroński, S., Hubacz, R., *Mass transfer in gas-liquid Couette-Taylor reactor,* Chem. Eng. Sci., 2000, in press.
5. Kataoka, K., [in:], *Encyclopedia of Fluid Mechanics*, Chapter 9, pp. 257. Cheremisinoff Ed., Golf Publishing Company, Houston, 1986.