REVIEW

A NOTE ON THE INTENSIFICATION OF HEAT AND MASS TRANSFER IN INTERACTING GAS AND LIQUID SYSTEMS

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At the first session, held in 1964, of the Scientific Committee on the Theoretical Basis of Chemical Engineering of the Academy of Sciences USSR, it was resolved to accelerate investigations and to develop methods of calculation in the field of heat and mass transfer processes (rectification, absorption, extraction, etc.) under intensified conditions.

Heat and mass transfer processes, which are based on the interaction of gas and liquid systems, may be intensified not only by optimization of the physical and chemical conditions, but also, to a considerably greater degree, by creating favorable hydrodynamic conditions. These processes are described, as a rule, by the diffusion kinetics, which additionally cause their intensity to depend on the hydrodynamic conditions. For example, investigations of mass transfer in film-type rectification equipment [1] showed that the coefficients of mass transfer between the liquid and vapor phases for a whole series of mixtures was independent of the concentration, but varied strongly with variation of the velocity of the vapor and the liquid.

The objective of the present paper is to elucidate, by systematic examination of the data of a number of sources, the state of investigations devoted to a study of the intensification of heat and mass transfer processes during interaction of gas and liquid systems in equipment with high-speed gas flow.

Investigations have been conducted [2–4] of film absorption and rectification in equipment with high-speed single-pass gas motion. It has been established that the degree of intensification of the hydrodynamic state of interacting systems is limited by the following factors: a) increase of hydraulic resistance of the contact element, and b) decrease in the efficiency of the contact stage due to removal of the liquid phase, arising with increased gas flow velocities.

The most promising method for increase of heat and mass transfer has proved to be the use of swirling flow. Swirling flow is an artificial type of motion, formed when a gas or liquid stream is supplied to a contact heat exchanger through tangential slits or swirl rosettes (spiral and screw inserts, etc.).

This type of stream may have constant swirl pitch—in the case where the swirl element is installed along the whole length of the equipment, or variable pitch—where there is a swirl element or tangential inlets only at some initial section.

Any swirling stream is characterized by the tangential velocity component profile, the flow structure and the degree of swirl being dependent on its variation. The swirl parameter usually taken is the ratio of the rotational to axial velocity. The magnitude of the swirl depends mainly on the angle at which the stream is injected and the conditions of injection. The first papers on the use of swirling flow pointed out the high efficiency of this method of intensifying heat and mass transfer.

An investigation of convective heat transfer in a tube under swirling flow conditions [5], with pitch varying along the length, i.e., with swirl devices mounted at the initial section, has shown that the heat transfer increases with increase of entry angle φ. The enhancement is greater in the initial section of the tube at $l/d < 40$ (l is distance from the inlet).

In the Re number range examined, in a section of tube $l = 20d$, in swirling flow conditions, with entry angle $\varphi = 90°$, an increase of Nu number was obtained of a factor of 3.8 relative to flow without swirl, for a resistance increase of a factor of 6, allowing for entrance losses.

However, a more valid comparison of swirling and nonswirling flow is based on the amount of heat transmitted through the same heater surface, with the same power expended in overcoming resistance to motion of the medium in the tube.

Calculations have shown [5] that, from the viewpoint of energy usage, strongly swirling streams give a gain in heat transfer of 60–73% compared to nonswirling streams, under the same expended power and temperature conditions. A similar increase in heat transfer coefficient was obtained in investigations of tubular heat exchangers, using twisted strips as swirl generators [6]. The favorable influence of flow swirl on heat transfer has also been verified for screw motion of a liquid [7].

Investigations of cyclone heat exchangers [8] has also indicated a considerable enhancement of heat transfer in swirling flow, and has permitted the construction of quite efficient equipment [9, 10].

A number of authors [5, 6, 8] have given empirical correlations for a quantitative evaluation of the favorable influence of flow swirl.

For a circular tube the equation obtained is

$$\mathrm{Nu} = \mathrm{Nu}_{\infty}\left(1 + k\,\frac{d}{l}\right),$$

where Nu_{∞} is the Nusselt number for nonswirling flow, and k is a coefficient indicating the degree of intensification of heat transfer, determined from experiment.

Analysis of the formula presented shows that the intensification is more strongly apparent in the initial section of the tube, i.e., where the most flow swirl is achieved. Hence it follows that for an efficient form of construction one should strive for constant or only slightly diminishing flow swirl. On the basis of the foregoing, it may be suggested that an ascending swirling stream should be more efficient than a descending one, for which straightening proceeds more rapidly.

From analogy with heat transfer, it should be expected that flow swirl promotes intensification of mass transfer processes also.

In actual fact a number of papers has been published in recent years dealing with this topic, in which, in addition to experimental results, recommendations have been given for construction of equipment to achieve intensified mass transfer.

Intensification of mass transfer has been investigated as an example of evaporation of previously heated liquid from the surface of a film inside a cylindrical tube by means of swirling gas flow [11–13].

The author has made a comparison of the mass transfer coefficient obtained from tests with that calculated from the equation

$$\mathrm{Nu}_D = 0.019\mathrm{Re}^{0.4},$$

which is ordinarily used to calculate mass transfer from the surface of a film of water in nonswirling flow.

The conclusion was drawn, based on test data, that, for the range of Re numbers investigated, the mass transfer coefficient was greater, by a factor of 4 on the average, than for the usual nonswirling stream, and the hydraulic resistance by a factor of 7, on the average.

Comparatively recently, investigations were made of the hydrodynamics and mass transfer in models of single-pass contact heat exchangers, in which rotary motion was imparted to a descending stream of gas and liquid [13–15]. The investigations showed the presence of two hydrodynamic regimes in the heat exchanger: jet-like and disperse. The existence of these regimes depends on the flowrate of the liquid phase. In addition, reduction of the test data to parametric form showed that Eu does not depend on Re, i.e., the range of operation of the equipment investigated lies in the self-similar region. For each regime an empirical parametric equation of the type $\mathrm{Eu} = f(\mathrm{Re}_l; h/s)$ has been put forward, where s and h are the pitch and length of the screw swirl generators.

Investigations of mass transfer in absorption of NH_3 and CO_2 have given adequate confirmation of the effectiveness of swirling flow. In the absorption of carbon dioxide by water, the screw motion of the gas and liquid stream enables the contact area of the phases to be increased, and the mass transfer to be intensified by a factor of 2–2.5, in comparison with a nonswirling stream.

In the case of a descending, swirling, two-phase stream in the absorption of CO_2 by water, empirical relations for mass transfer coefficients have been proposed [14, 15] of the type

$$K_{al} = f(\mathrm{Re}_l;\ w_g),$$

relating the mass transfer coefficients with the spray density and the gas velocity. Calculations of the authors show that, with gas velocity $w_g = 23.2$ m/sec, the mass transfer coefficient is 25 times larger than the maximum coefficients in counterflow tubular film columns, at the same spray density, for the case of absorption of a sparingly soluble gas. In the test model the free section of the contact equipment was 19.8% of the section of the apparatus. With this proportion, the authors reduced the velocity in the free section of the contact equipment to 35.3 m/sec, which corresponds to 7.00 m/sec, calculated on the total section of the apparatus.

At present, investigators have various explanations for the cause of the more effective heat and mass transfer of a two-phase stream. One [11] sees the reason in the fact that a thin jet of gas with considerable velocity flows over the mass-emitting surface, and others in the fact that the use of a swirling stream considerably increases the duration of contact between the phases [3]. According to [1], the mass transfer intensity is increased with decrease of wavelength on the film surface.

By analogy with the aerodynamic picture of two-phase flow in cyclone equipment [8], where the ratio of the circular to axial velocity falls in the range 2–3, it may be asserted that the true velocity of motion of the layers of the two-phase stream on the surface of the twisted film is several times greater than the axial velocity. Then, because of the tangential forces on the film surface, there will inevitably be increased vortex and wave formation.

The known relation for wavelength, proposed by Kapitsa [16], which may be applied in the case examined, with some approximation and only for a qualitative estimate, is

$$\lambda = \frac{2\pi}{\bar{u}_l}\sqrt{\frac{\sigma Y_0}{\rho_l (z-1)(z-a)}},$$

where $\bar{u}_l$ is the mean liquid velocity; σ is the surface tension; ρ_l is the liquid density; Y_0 is the mean film thickness; and z is the ratio of the wave phase velocity to the mean liquid velocity. This relation indicates that the wavelength decreases as the velocity of the two-phase stream increases.

These hypotheses are confirmed in part by investigations of single-pass motion of a two-phase nonswirling stream [17]. These investigations of liquid film flow in a nonswirling stream have shown that the mean linear velocity of the film has a maximum value at the crest of the wave ($v = 1.4\ v_0$), and a minimum at the trough ($v = 0.5\ v_0$). Therefore, for definite values of the wavelength λ, a local variation occurs in the direction of the liquid stream, i.e., vortices are formed which promote intense mass transfer. It is evident that the smaller λ, the larger the vortex that arises in a given segment of film.

Thus, the phenomenon of wave and vortex formation on the phase contact surface promotes a considerable increase of heat and mass transfer. It has been proved experimentally that the first of the above factors is dominant [18].

Most authors have studied mass transfer in a single contact stage. In order to use multistage contact equipment with swirling flow, it will evidently be necessary to solve the problem of separating the liquid from the gas. In the counterflow case, with the high gas velocities obtainable over the cross section of the equipment by virtue of the swirling stream, a decrease in efficiency of the contact stages is possible because of the removal of liquid. The most efficient and economical solution of the problem proves to be use of the centrifugal force from the swirl of the stream itself for separating the liquid.

So far, investigations on intensification of mass transfer have been conducted in a comparatively weakly swirling descending stream, which is characterized by some attenuation of the swirl and, therefore, by some decrease in the effectiveness of the swirling stream along the contact elements.

It would be appropriate in future to investigate the hydrodynamics and mass transfer in an ascending swirling stream, which should be more effective than a descending stream, because of the tightening of the swirl.

SUMMARY

1. The use of a swirling stream permits intensification of heat transfer; the effectiveness of a swirling stream and the hydraulic resistance depend on the swirl of the stream.

2. The use of a swirling stream permits intensification of mass transfer. In the absorption of a sparingly soluble gas, in particular, the process is more intense by a factor of 2–2.5 than in a nonswirling stream.

3. The use of a swirling stream also permits considerable gas phase velocity in contact equipment over the total section of the apparatus. Contact devices using swirling flow can achieve phase separation at considerable gas phase velocities over the whole section of the equipment.

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