FLOW OPTIMIZATION BY FLOW REDISTRIBUTORS IN WETTED REACTOR II

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General procedure is proposed for flow optimization inside the packing of wetted reactors by use of flow redistributors. Improvement of efficiency and life time of packing are illustrated on the example of the refining hydrogenation reactor, where the flow inside the packing in the wall region is in equilibrium with the wall flow.

Suitable distributions of wetting density on the active part of the bed of catalyst and the wall flow problems[2-4] are of great importance in the design of wetted reactors[1]. The first group of problems is related to the design of the primary distributor *i.e.* how the liquid is fed to the top of the packing in wetted reactor, the second is related to the problem of construction and suitable location of flow redistributors.

THEORETICAL

Solution of the above mentioned problems is based on quantitative relations which are obtained by solution of partial differential equations for the mechanism of diffusion flow

$$\frac{\partial I}{\partial z} = D \,.\, \nabla^2 I \,, \tag{1}$$

where ∇^2 is the two-dimensional Laplace operator applied to the wetted plane.

For the given initial distributor and the liquid transfer mechanism in the wall region Eq. (*1*) can be integrated analytically, while we obtain the solution expressing the dependence of the wetting density on location of the considered point in the reactor packing.

At the assumption of axial symmetry and at the use of cylindrical coordinates we obtain by solution of Eq. (*1*) the relation

$$\frac{I}{I_0} = \frac{1}{K+1} + \sum_{n=1}^{\infty} A_n J_0\left(\frac{r}{a}\, q_n\right) . \exp\left(-\frac{Dz}{a^2}\, q_n^2\right), \tag{2}$$

where q_n are roots of the equation

$$J_1(q) + f(q) \, . \, J_0(q) = 0 \, . \tag{3}$$

The form of coefficients A_n of the infinite series (2) depends on the initial liquid distribution. The function $f(q)$ in Eq. (3) depends on the shape of the boundary condition ($r = a$) *i.e.* in which way we express the mechanism of liquid transfer between the wall of the wetted equipment and the packing of the active bed of the reactor. If we use the boundary condition which is expressing the behaviour of the wall as the total reflector[5] we obtain $f(q) = 0$. If we express the real existence of the wall flow and the dynamics of its formation *i.e.* if we apply the boundary condition[6]

$$-D\left(\frac{\partial I}{\partial r}\right)_{r=a} = \beta(I(r = a) - l \, . \, w) \, , \tag{4}$$

we obtain Eq. (5) in the dimensionless form

$$-H\left(\frac{(I/I_0)}{(r/a)}\right)_{r/a=1} = K\left(\frac{I}{I_0}\right)_{r/a=1} - \frac{\dot{V}_s}{\dot{V}_0} \, , \tag{5}$$

where

$$H = 2D/\beta la^2, K = 2/la, \dot{V}_s = 2\pi a \, w, \dot{V}_0 = \pi a^2 I_0 \, .$$

The concrete function $f(q)$ is given in our previous study[7]. Individual concrete solutions of density distribution in the packing of the reactor for the most frequent initial sources and boundary conditions are given in other studies (wall as the total reflector[5]), wall flow in equilibrium with the flow in the packing at the wall[8] and the boundary condition (4) (ref.[6]).

Though the published relations enable expression of wetting density in an arbitrary point in the reactor, as concerns their optimization and design, it is better to express the curves of constant liquid flow from the published relations. From their graphical representation it is then possible to calculate directly the regions of overloading or underestimation of the catalytic bed both from the points of view of the packing as well as of liquid flow.

From the mathematical point of view we solve the function

$$z = z(I, r) \tag{6}$$

or

$$r = r(I, z) \, . \tag{7}$$

If we introduce the function

$$y = I_x - I(z, r_k) \tag{8}$$

we can determine numerically the curves of constant liquid flow rate *i.e.* by determination of roots of Eq. (*8*) (for the given I_x and r_k we look for z so that $y = 0$).

In view of requirements on the computation time, it is advantageous to look for the numerical solution of function (*6*) when

$$z = z(I_x, r_k) \tag{9}$$

where the index x means that a certain curve, with the constant liquid flow rate is calculated and index k with r means that only the point of intersection of this curve with the given radius of the equipment is calculated (or its z-th coordinate).

Practical Computations and the Used Mathematical Relations

As the refining hydrogenation reactor is a frequently used type of wetted reactor with a relatively small wall flow[9,10], the relations can be used for illustrative calculation of curves of constant flow in this reactor, which solve Eq. (*1*) with the boundary condition

$$I(r = a) = I \, . \, w \tag{10}$$

according to which the flow in the region of contact of the packing with the wall is in equilibrium with the wall flow. The boundary conditions characterizing the geometric parameters of the primary liquid distribution are given by Eqs (*12b, c*) (Fig. 1*a*).

According to the procedure described in the earlier study[7] we obtain for the liquid fed centrally through the distributor with the radius r_1 the following relation

$$\frac{I}{I_0} = \frac{1}{K + 1} + \frac{8}{r_1/a} \sum_{n=1}^{\infty} \frac{J_1(r_1 q_n/a)}{q_n(4 + 4K + K^2 q_n^2) \, J_0^2(q_n)} \, J_0\left(\frac{r}{a} q_n\right) . \exp\left(-\frac{Dz}{a^2} q_n^2\right) \tag{11}$$

valid for the boundary conditions (*12a–c*)

$$\left(\frac{\partial I}{\partial r}\right)_{r=0} = 0 \, , \quad I(0 \leqq r \leqq r_1) = I_0 \, , \quad I(r_1 < r < a) = 0 \, , \tag{12a, b, c}$$

where q_n are roots of equation

$$2J_1(q) + Kq \, J_0(q) = 0 \, . \tag{13}$$

We then calculate by the procedure described in the recent study[7] the liquid distribution for the general j-th redistributor which is described by the boundary conditions (*12a*) and (*14*) (Fig. 1*b*)

$$I_j(0 \leqq r < r_{1,j}) = \frac{I_0}{K+1} + \sum_{n=1}^{\infty} B_{n(j-1)} I_0 J_0\left(\frac{r}{a} q_n\right) . \exp\left(-\frac{Dz_{0j}}{a^2} q_n^2\right) \quad (14a)$$

$$I_j(r_{1,j} \leqq r > a) = I_0 \left(\frac{a^2}{2r_{1j}} - \frac{r_{1j}}{2(K+1)} - \frac{a^2}{r_{1j}} \sum_{n=1}^{\infty} B_{n(j-1)} \cdot \frac{r_{1j}}{aq_n} \cdot \right.$$
$$\left. . J_1\left(\frac{r_{1j}}{a} q_n\right) . \exp\left(-\frac{Dz_{0j}}{a^2} q_n^2\right) . \delta(r - r_{1j}) \right), \quad (14b)$$

where $B_{n(j-1)}$ represents the constants in the relation for $(j-1)$st redistributor (or source).

For the j-th redistributor there holds $(j = 1, 2, \ldots)$

$$\left(\frac{I}{I_0}\right)_j = \frac{1}{K+1} + \sum_{i=1}^{\infty} A_{ij} . J_0\left(\frac{r}{a} q_i\right) . \exp\left(-\frac{Dz}{a^2} q_i^2\right), \quad (15)$$

where

$$A_{ij} = 4/[q_i(4 + 4K + K^2 q_i^2)\, J_0^2(q_i)] \cdot \left\{\frac{1}{K+1}\left\{\left[K + 1 - \left(\frac{r_{1j}}{a}\right)^2\right] q_i\, J_0\left(\frac{r_{1j}}{a} q_i\right) + \right.\right.$$
$$+ 2\frac{r_{1j}}{a} J_1\left(\frac{r_{1j}}{a} q_1\right)\right\} + 2\frac{r_{1j}}{a} q_i^2 \sum_{\substack{n=1\\ n \neq i}}^{\infty} A_{n(j-1)} . \exp\left(-\frac{Dz_{0j}}{a^2} q_n^2\right) \left\{\frac{1}{q_n(q_n^2 - q_i^2)} \cdot \right.$$
$$\left. \cdot \left[q_i\, J_0\left(\frac{r_{1j}}{a} q_i\right) . J_1\left(\frac{r_{1j}}{a} q_n\right) - q_n\, J_0\left(\frac{r_{1j}}{a} q_n\right) . J_1\left(\frac{r_{1j}}{a} q_i\right)\right]\right\} +$$

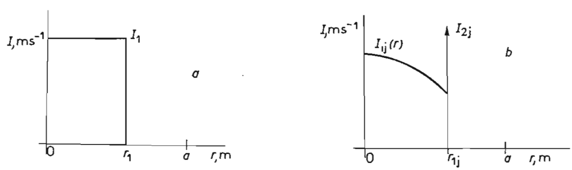

FIG. 1

Central Source *a* and the General Redistributor *b*

$$+ \frac{r_{1j}}{a} A_{i(j-1)} \cdot \exp\left(- \frac{Dz_{0j}}{a^2} q_i^2\right) \left\{ \frac{r_{1j}}{a} \left[J_0^2 \left(\frac{r_{1j}}{a} q_i\right) + J_1^2 \left(\frac{r_{1j}}{a} q_i\right)\right] q_i - \right.$$
$$\left. - 2J_1 \left(\frac{r_{1j}}{a} q_i\right) . J_0 \left(\frac{r_{1j}}{a} q_i\right) \right\}\Bigg\} \qquad (16)$$

and

$$A_{i0} = \frac{8\, J_1((r_{1j}/a)\, q_i)/(r_1/a)}{q_i(4 + 4K + K^2 q_i^2)\, J_0^2(q_i)}\,, \qquad (17)$$

where z_{0j} is the distance between the j-th and $(j-1)$st redistributor for $j = 2, 3, \ldots, z_{01}$ is the distance of the first redistributor from the primary source, r_{1j} is the radius of the j-th redistributor for $j = 1, 2, \ldots, r_1$ is the radius of the central primary distributor, q_i, q_n are roots of Eq. (*13*). Relation (*16*) is applying directly the relation (*32*) given in our previous study[7] for H=0.

Relations (*14*) and (*12*) were used in Eq. (*8*) by substitution $(I/I_0)_j$ for $I(z, r_k)$.

RESULTS AND DISCUSSION

Active action of processes taking place in the wetted equipment is possible on basis of the computations performed according to the proposed procedure. It is possible to proceed so that we limit from the kinetic calculations or experimental measurements the regions of optimum flow density, transition regions with the still suitable density and regions with the unsuitable flow density *i.e.* considerably underestimated or

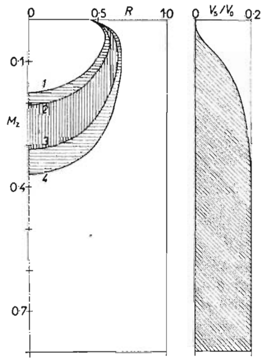

FIG. 2

Curves of Constant Liquid Flow in the Wetted Reactor Without the Use of Flow Redistributor

Primary redistributor: central $(r_1/a) = 0{\cdot}6)$, $K = 0{\cdot}25$, $H = 0$. Curves of constant liquid flow rate *1* region of unsuitable flow rate, *2* suitable intensity, *3* optimum intensity, *4* small intensity.

overestimated. These regions are limited by curves with constant liquid flow. However, the calculation of these curves means determination of the radius r and height z so that the flow intensity given by the infinite series be constant. As it is not possible to express explicitely $r = r(z, I)$ or $z = z(r, I)$ it is necessary to perform this computation numerically. The results of these numerical calculations are plotted in Figs 2 to 4, where the wall flow is also demonstrated.

In Fig. 2 is demonstrated the cross section of one half of the reactor with the coordinates in the dimensionless form. The geometric and hydrodynamic parameters are: dimensionless height of the packing 0·8, primary central source with the dimensionless radius 0·4, criterion $K = 0{\cdot}25$ *i.e.* the equilibrium wall flow is 20% of the total flow, criterion H=0, the region of optimum dimensionless intensity is chosen between 0·9 and 1·15 (vertical cross-hatching), the region of suitable intensity 0·85–0·9 and 1·15–1·3 (horizontal cross-hatching). The regions with the intensity smaller than 0·85 (unhatched) can be considered to be the regions of not active packing, region with the intensity greater than 1·3 (oblique cross-hatching) are regions of overloaded packing or not fully utilized liquid. It is also suitable to study the liquid flow on the wall. The dependence of the wall flow is plotted in the right part of Figs 2–4. It can

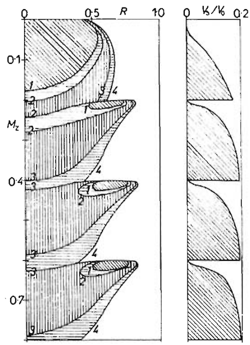

FIG. 3

Curves of Constant Liquid Flow Rate in Wetted Reactor Without the Use of Flow Redistributors

Primary distributor: central ($r_1/a = 0{\cdot}6$), $K = 0{\cdot}25$, $H = 0$, $r_{1j}/a = 0{\cdot}7$, $Dz_{0j}/a^2 = 0{\cdot}2$ (j represents the j-th redistributor).

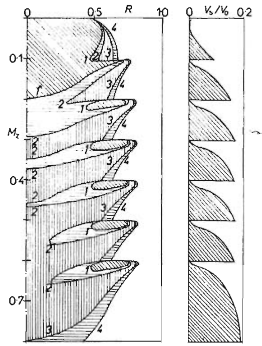

FIG. 4

Curves of Constant Liquid Flow Rate in the Wetted Reactor at the Use of Flow Redistributors

Primary distributor: central ($r_1/a = 0{\cdot}6$), $K = 0{\cdot}25$, $H = 0$; $r_{1j}/a = 0{\cdot}7$, $Fz_{0j}/a^2 = 0{\cdot}1$.

be also seen from Fig. 2 that the greater part of the reactor can be considered to be the region of not utilized packing. The situation improves by application of flow redistributors. This situation is demonstrated in Fig. 3 where application of three redistributors (with the dimensionless radius 0·7) considerably increases the optimum and transition regions in comparison to the reactor without redistributors. The life time of the packing and efficiency of the operation became considerably greater.

Application of six redistributors is demonstrated in Fig. 4, with the dimensionless radius 0·7. We can see again a considerable improvement of hydrodynamic conditions and better utilization of the active packing of the wetted reactor.

Finally it is possible to conclude that according to the proposed procedure conditions in the wetted units can be improved actively. It is obvious that the illustrative example of the proposed procedure in this publication can be used also in systems where the dynamics of formation of the wall flow ($H \neq 0$) must be also taken into consideration. The procedure in such cases will be the same, only the relations which must be used for numerical calculations of isoflows will be more complicated.

LIST OF SYMBOLS

$A_i, A_n, A_{ij}, A_{i(j-1)}, A_{n(j-1)}, A_{i0}$	coefficients of terms of the infinite series
a	radius of the reactor, m
$B_{n(j-1)}$	coefficients of terms of infinite series
D	spreading coefficient of liquid on the packing, m
$f(q)$	function given by the liquid transfer mechanism in the wall region
H	criterion of dynamics of liquid transfer at the wall
I, I_x	wetting density, ms^{-1}
I_0	mean wetting density, ms^{-1}
J_0, J_1	Bessels' functions
K	criterion characterizing the magnitude of the equilibrium wall flow
l	constant characterizing the magnitude of the equilibrium wall flow, m^{-1}
M_z	dimensionless packing height
q_i, q_n	roots of the transcendent equation given by the liquid transfer mechanism in the wall region
r, z	cylindrical coordinates (origin in the point of last flow redistributor or source), m
r_k	radius, whose point of intersection with the constant flow curve is being calculated, m
r_1	radius of central source, m
$r_{1j}, r_{1,j}$	radius of the j-th redistributor ($j = 1, 2, \ldots$), m
$\dot{V}_s$	wall flow rate, $m^3 s^{-1}$
$\dot{V}_0$	total liquid flow rate through the reactor, $m^3 s^{-1}$
w	density of wall flow, $m^2 s^{-1}$
y	auxiliary function
z_{0j}	distance of the j-th and (j-1)st redistributor ($j = 2, 3, \ldots$), or between the first redistributor and primary source ($j = 1$), m
β	rate constant of reaching the equilibria between the wall flow and liquid flow in the packing at the wall
δ	Dirac's function, m^{-1}

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