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NUMERICAL STUDY ON THE OPERATIONAL PERFORMANCE OF SPRAY COLUMN DIRECT CONTACT HEAT EXCHANGERS

Chong Bo Kim* and **H.R Jacobs****

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Spray columns have received considerable attention as direct contact heat exchangers due to their potential high throughput, as well as their near perfect counterflow operations if one-dimensional flow is obtainable. In practice, the degree of success in obtaining one-dimensional flow has depended on the design of the injectors for the disperse and continuous phases. In the past, the design of the injectors have been a trial and error procedure not sufficiently backed up by analyses. In this paper, theoretical analyses are carried out and several designs are evaluated. The influence of proper inlet conditions for the continuous phase to assure near one-dimensional flow is illustrated.

Key Words : Spray Column, Direct Contact Heat Exchanger, Continuous Phase Flow, Dispersed Phase, Injection

NOMENCLATURE

A_c : Inlet opening area
b : Diameter of dispersion plate
d : Diameter of inlet piping
D : Diameter of spray column
G_c : Flow rate of continuous phase flow
h : Height of lateral inlet opening
ℓ : Length of inlet piping
L : Length of spray column
ν : Kinetic viscosity of continuous phase fluid
ρ : Density of continuous phase fluid
r : Radial coordinate
r_o : Column radius
R : Dimensionless radial coordinate
Re_D : Reynolds number based on column diameter
u_r : Radial velocity
u_z : Axial velocity
u_o : Inlet discharge velocity
U : Dimensionless axial velocity
v : Dimensionless radial velocity
z : Axial coordinate
Z : Dimensionless axial coordinate
ψ : Stream function
Ψ : Dimensionless stream function
Ψ_1 : Dimensionless stream function at the nearest node above the rigid wall
Ψ_2 : Dimensionless stream function at the second nearest node above the rigid wall
Ψ_0 : Dimensionless stream function at the centerline
Ψ_W : Dimensionless stream function at the rigid wall
ω : Vorticity
Ω : Dimensionless vorticity
Ω_W : Dimensionless vorticity at the rigid wall

1. INTRODUCTION

The spray column has been widely studied in the chemical industry for many years due to its inherent simplicity as a counter-current device for heat or mass transfer. Developments were enhanced in the 1960's due to increased interest in desalination system(Kellogg Company, 1971).

More recently, in the 1970's, Jacobs and Boehm(1980) suggested their use for extracting heat from moderate temperature geothermal brines. Based upon the relative success of this application, a number of other applications have been spawned. Most closely related is the use of a modified spray type direct contactor for the extraction of heat from a salt stratified solar pond. Although both geothermal and solar pond applications have the same ultimate purpose, to generate electricity from a moderate to low temperature source and to obtain the energy exchange at small approach temperature differences, many source related characteristics caused significant differences in their design. For the geothermal applications, it has generally been conceded that the most economical design is to utilize as much heat as possible from each unit mass of geothermal brine. This leads to near equal mass flow rate of the working fluid and brine. For solar ponds the brine is available at temperatures of 100°C or less, which leads to a relatively low flow rate of the working fluid, typically, pentane, as compared to the flow of brine.

In most common applications, each fluid is in a liquid phase ; however, for binary power cycles, a single column can include a liquid preheating zone and a boiling or evaporation zone. In order to design a direct contact heat exchanger of the spray column type, it is necessary to design a distributor which can produce regular uniform-sized drops of one of the two fluids. Normally this is the lighter fluid. This is achieved by designing a distributor which uses a perforated plate of a material not wetted by the dispersed phase fluid.

Spray column liquid-liquid heat exchanger experiments have been conducted for the following fluids as the dispersed phase with water as the continuous phase : benzene(Garwin and Smith, 1953), toluene(Treybal, 1953), CCl_4(Johnson et. al, 1957), shell oil A and spray base(Woodward, 1961), mercury(Pierce, Dwyer, and Matying, 1959), isobutane(Suratt, and Hart, 1977) and pentane(Goodwin, Coban, and Boehm, 1985). This data has been used by various investigators to obtain volumetric heat transfer coefficients. The volumetric heat transfer data have, in general, been presented as a function of holdup. Following the lead of Letan and earlier investigators(Letan, 1976, Letan and Kehat, 1968), Plass, Jacobs and Boehm(1979) ran a series of experiments to determine a volumetric heat transfer coefficient, U_v. They correlated both their own data and that of other investigators for organic fluids dispersed in water or geothermal brine.

The design for the dispersed phase injector is reasonably straightforward and is essentially a perforated plate covering a manifold. The injection of the continuous phase is more difficult and flaws in its design are probably the leading cause of axial circulation in a liquid-liquid spray column ;

* Department of Mechanical Engineering, Inha University, Inchon 160, Korea
** Department of Mechanical Engineering, Pennsylvania State University, P.A. 16802, U.S.A.

although, a degree of the axial mixing is caused by wakes of individual drops rising and being shed by the individual drops(Goodwin, 1985, Loutaty 1969). However, it should be noted that little research on internal back mixing or axial mixing has been done.

In the analyses of spray columns, models currently used are one-dimensional and either transient or steady state(Jacobs and Golafshani, 1985, Golafshani and Jacobs, 1985). Steiner and Hartland(1983) carried out experiements in a spray column without and dispersed phases present. They noted strong circulation in the continuous phase only. Such was the problem, it was believed with the early operation of the 500 KW_e spray column direct contactor at East Mesa(Olander, et al, 1983). However, changes in other operating conditions were also made at the same time as the injector was changed. Thus no one knows for sure where the injector modification alone led to improved operation. Therefore, it was deemed essential to develop a two dimensional axisymmetric flow model in order to determine the hydrodynamic behavior of the continuous flow. Using this model, general guidelines can be obtained to provide design information for the continuous phase injector.

2. MATHEMATICAL MODELING

Consider a spray column, as shown in Fig. 1, where the column diameter is much larger than the drop size and the column length is much larger than the diameter. If the injectors and exit ports are symmetrically located it is reasonable to assume that the flow will be axisymmetric. Assuming further a low ratio of the dispersed phase to the continuous phase, it is reasonable to study the continuous phase flow patterns by assuming them to be independent of the dispersed phase.

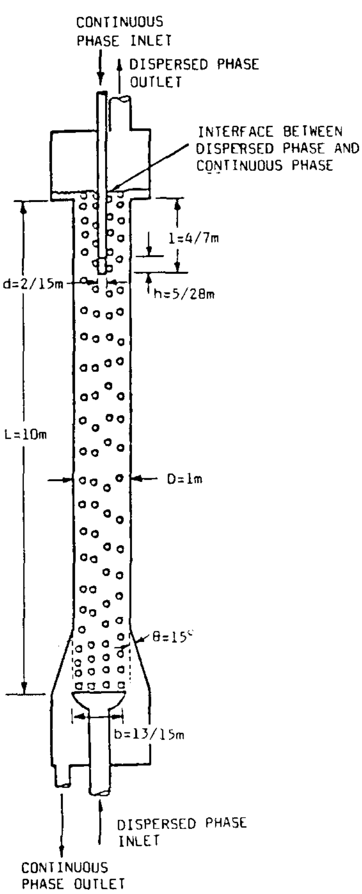


Fig. 1 Direct contact spray tower for liquid-liquid heat exchange

Assuming the flow to be steady state and O.K. as well as axisymmetric, we can solve the governing equations for the given geometry representing the physical model. Using the stream function-vorticity method, the continuity equation is satisfied when the axial and radial velocity components are expressed as:

$$U_z=\frac{1}{\gamma}\frac{\partial\psi}{\partial\gamma},\quad U_\gamma=-\frac{1}{\gamma}\frac{\partial\psi}{\partial z} \tag{1}$$

The equation of motion for a steady incompressible fluid is

$$\vec{v}\times\vec{\omega}=\nabla\left(\frac{P}{\rho}+\frac{1}{2}V^2\right)+\nu\nabla\times\vec{\omega} \tag{2}$$

and the vorticity equation is

$$\nabla\times(\vec{v}\times\vec{\omega})=-\nu\nabla\times\nabla\times\vec{\omega} \tag{3}$$

Where $\nabla\times\vec{v}=\vec{\omega}$ is the vorticity.

By utilizing r_o, U_o quantities as the reference, the following dimensionless variables are introduced

$$R=\frac{\gamma}{\gamma_o},\ Z=\frac{z}{\gamma_o},\ U=\frac{U_z}{U_o},\ V=\frac{U_\gamma}{U_o} \tag{4}$$

$$\Psi=\frac{\psi}{\gamma_o^2U_o},\ \Omega=\frac{-\omega}{U_o/\gamma_o},\ Re=\frac{u_o\gamma_o}{\nu}$$

In terms of these new variables, the governing equations for an axisymmetric configuration become

$$U=\frac{1}{R}\frac{\partial\psi}{\partial R} \tag{5}$$

$$V=-\frac{1}{R}\frac{\partial\psi}{\partial z} \tag{6}$$

$$\left[\frac{\partial^2}{\partial R^2}-\frac{1}{R}\frac{\partial}{\partial R}+\frac{\partial^2}{\partial R^2}\right]\Psi=R\Omega \tag{7}$$

$$\frac{\partial(V\Omega)}{\partial z}+\frac{\partial(V\Omega)}{\partial R}=\frac{1}{Re}\left[\frac{\partial^2}{\partial R^2}+\frac{1}{R}\frac{\partial}{\partial R}-\frac{1}{R^2}+\frac{\partial^2}{\partial z^2}\right]\Omega \tag{8}$$

The stream function Ψ must have a constant value along the whole boundary wall length; the specification of this value constitutes the boundary condition on Ψ for that part of the boundary.

Along the symmetry axis of the flow the stream function must also be a fixed value. This condition expresses the fact that the radial component of velocity must be zero at the axis. Moreover, the gradient of Ψ must also be zero. So $\frac{\partial\psi}{\partial R}$ must tend to zero at the same rate as R near the axis; and symmetry demands that the second term in the Ψ-R expansion should be the fourth-power one(Gosman, et al, 1969); thus

$$\Psi-\Psi_o\approx a\,R^2+b\,R^4 \tag{9}$$

where Ψ_0 is the stream function at the axis, and a and b are constants, for fixed z.

It is rare for the vorticity at the wall to be specified or even the vorticity gradient along the normal line. The boundary condition for the vorticity therefore has to be deduced from other information; usually this is the requirement that there should be no slip between the wall and the fluid adjacent to it. By using a second order approximation(Gosman et. al, 1969) the vorticity at the wall can be approximated by

$$\Omega_{wall}=\frac{-7\Psi_{wall}+8\Psi_1-\Psi_2}{2(\Delta R)^2} \tag{10}$$

It is an implication of the above, and of the vorticity equation, that the vorticity at the axis must be zero. Ω/R, on the other hand, may be finite.

The condition of the entering fluid is assumed known. If the entrance flow is uniform, Ω at the entrance is zero. Rather more care is needed in the setting of the boundary conditions for the outlet flow. Assuming the outflow to be uniform, the following conditions for the vorticity and stream function are obtained.

$$\left.\frac{\partial \Psi}{\partial z}\right|_{outflow} = 0 \tag{11}$$

$$\Omega|_{ouoflow} = \frac{1}{R}\frac{\partial^2 \Psi}{\partial R^2} - \frac{1}{R^2}\frac{\partial \Psi}{\partial R} \tag{12}$$

In this paper, three different inlet/exit conditions are considered to evaluate the influence of injector orientations on the flow characteristics. These include both axial and radial continuous phase injectors with a constant diameter column, and radial injection with a 15° expansion skirt at the column base.

In carrying out the numerical solutions, the stream function-vorticity equations were first converted into a set of algebraic equations using an hybrid differencing scheme. The finite difference method used closely follows that of Gosman, Spalding(1969), and Patankar(1980). The dimensions used in the calculation are similar to those of the $500KW_e$ spray column direct contactor at East Mesa(Olander et. al, 1983). The two continuous phase injector designs considered are also consistent with the one initially used(axial) and finally used(radial) at East Mesa. The outlet expansion skirt is the same as that used at East Mesa while the constant diameter column was that designed by the second author for the experiments described in Goodwin(1985). By using variable grids in z-direction and equal spacing in R-direction(21×15 grids). With given boundary conditions, the numerical solutions have been obtained. The iterations have been carried out for the residual value of 10^{-6}. Rapid convergence was obtained for all cases studied.

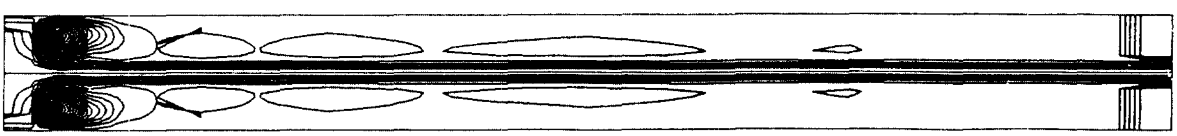
3. RESULTS AND DISCUSSION

In order to evaluate the effect of the flow rates and injector designs on the continuous phase flow, a geometry similar to the contact heat exchanger(Olander, 1983) (L=10m, D=1m) was considered(Fig. 1). The brine injector is located near the top of the column. An injector is designed to distribute the brine horizontally or vertically from a single tube. It yields a velocity of G_c/A_c from the inlet opening. The distribution plate is located in the conical frustrum section below the column proper where the diameter is less than the column diameter. In case of the one with 15° expansion skirt bottom, the diameter of the distribution plate is considered to be same as the column diameter.

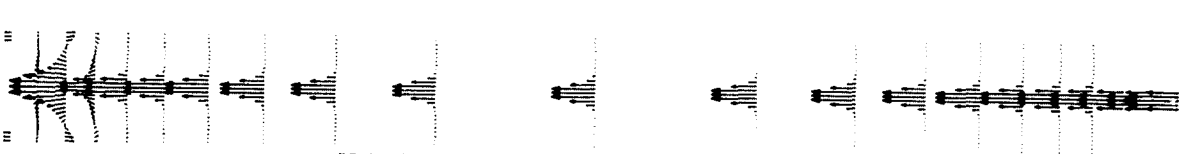
In this paper, three cases representing typical flows are investigated. The results are plotted for streamlines and velocity distributions along the column. Fig. 2 shows the results of axial injection. The continuous phase axial injection produces a recirculation region at the bottom. This recirculation exists for all flow rates typical of the $500KW_e$ unit operation. The axial jet penetrated all the way down to the bottom and maintains a near constant primary jet thickness along the center-line. Approaching the bottom, the jet accelerates and spreads a strong recirculation cell of the size of one-column diameter. This flow pattern was consistant for all flow Reynolds numbers examined ($2{,}300 \leq RE \leq 46{,}000$). Typical results are plotted for stream functions and velocity distributions along the column.

Figure 3 shows the results of radial injection with a plain bottom outlet. A radial injection of the continuous phase produced, for all flow rates, no recirculation cells. As soon as the flow leaves the inlet opening, the flow turns toward the bottom outlet opening and the flow becomes relatively uniform throughout the column.

Figure 4 shows the results of radial injection with a 15° expansion skirt at the bottom outlet. Comparison with the cases of radial injection with a constant diameter column indicates no significant changes in flow pattern for the same flow rates. This implies that there is no advantage in terms of the continuous phase flow patterns for the expansion skirt. However, there may be an advantage in terms of dispersed phase carrying out. Development of a two fluid

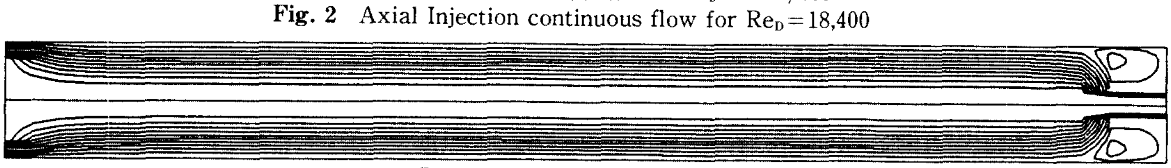


Stream function, Ψ, $\Delta\Psi = 0.4$

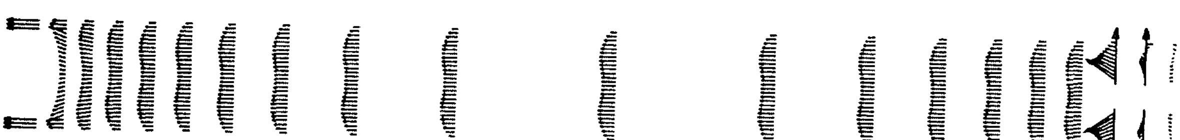


Velocity distribution, V(r, z), for $Vin_z = 0.4$m/sec

Fig. 2 Axial Injection continuous flow for $Re_D = 18{,}400$

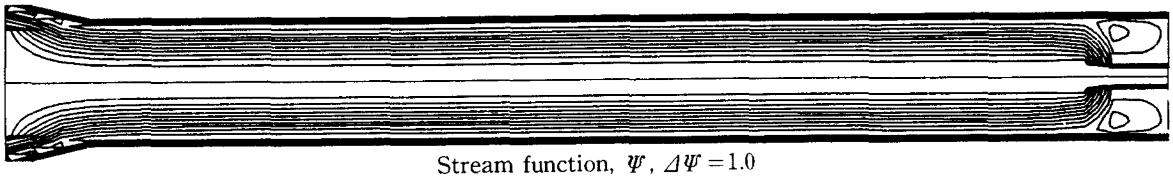


Stream function, Ψ, $\Delta\Psi = 1.0$

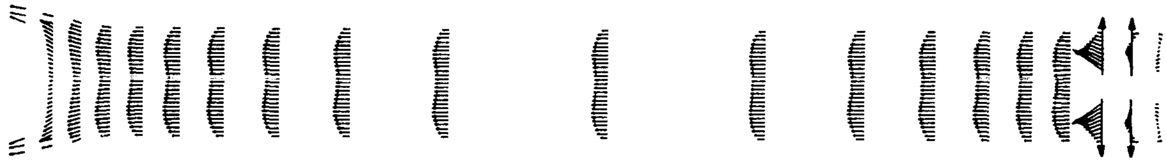


Velocity distribution, V(r, z), for $Vin_z = 0.4$m/sec

Fig. 3 Radial injection continuous flow for $Re_D = 46{,}000$



Stream function, Ψ, $\Delta\Psi = 1.0$



Velocity distribution, V(r, z), for $Vin_r = 0.4$m/sed

Fig. 4 Radial injection continuous flow with 15° expansion skirt for $Re_D = 46{,}000$

model is required to ascertain this phenomenon.

4. CONCLUSIONS

The design of the injectors of spray column direct contact heat exchangers has been investigated numerically by using a continuous phase two dimensional axisymmetric flow model. The stream function-vorticity method was adopted to obtain these solutions. Several designs were evaluated for a range of flow rates. Based on these results the following general guidelines are presented :

(1) Axial injection produces a strong jet concentrated on the center line of the column. The strong jet penetrates down to the bottom of the dispersion plate and produces recirculation flow cell of one column diameter high from the bottom plate. A strong jet and recirculation flow can lead to local flooding and potential break up of the dispersed phase drops ; thus, axial injection should be avoided.

(2) Radial release of the continuous phase provides a near uniform flow in the column. No recirculation cells were developed for any Reynolds number investigated. The radial injection method is therefore recommended as a method to supply continuous fluids into the spray column.

(3) Bottom expansion skirts appear to have little advantage over a consistant diameter column in terms of the continuous base flow patterns. Further investigations using a multiphase model are necessary to determine under what if any disperse phase to continuous phase flow conditions could benefit by the inclusion of a bottom expansion skirt.

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