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Separation of inclusions from liquid metal contained in a triangle/square pipe by travelling magnetic field①

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Abstract: By using plug flow and trajectory model, the elimination efficiency of the inclusions from liquid metals purified by travelling magnetic field (TMF) in either a triangle or a square pipe was analyzed theoretically. The ways to improve the elimination efficiency were suggested. The results using different kinds of pipes were reciprocally compared. It is determined that by means of TMF to eliminate inclusions the efficiency is affected by the diameter of the inclusions, in which the inclusions can be removed most efficiently, is optimized.

Key words: travelling magnetic fields; purification; inclusion **Document code:** A

1 INTRODUCTION

Generally the refined metals contain a large amount of non-metallic inclusions that come from the raw materials or arise from every step of the metal-making processes[1]. The size of the inclusion is usually small, and sometimes its density is close to that of the liquid metal.

A new technology which purifies the liquid metal with electromagnetic field emerges, whose principle is as follows[2~4]: put ceramic pipes containing liquid metal in the magnetic field, if the current is induced inside the liquid metal then the metal is subjected to an electromagnetic force (EMF). EMF can't act upon the non-metallic inclusions due to their poor conductivity, but the "pinch force" resulting from pinch of liquid metal around the inclusions acts on them. The direction of the "pinch force" is opposite to that of the EMF, so it causes the inclusions migrate toward the surface of the pipe and finally stick there. The advantage of this technology is that the micro inclusions, which are almost impossible to be removed through traditional floating mechanism, now may be fully eliminated.

Among the technologies used to purify metal by electromagnetic field, the one based on travelling magnetic field (TMF) has advantage of simple in equipment, no pollution by electrode and continuous in operation, so it seems most feasibly to be adopted in industry[5]. However, the research on this technology was not so far performed, so, this paper devotes to perform a theoretical analysis on the efficiency of separating inclusions from liquid metal flowed in either square pipes or triangle pipes.

2 MECHANISM OF PURIFYING LIQUID METAL USING TMF

Yoshiko[6] first suggested this technology as shown in Fig.1. Many ceramic pipes are set parallelly under the effect of TMF. Both ends of each pipe are connected to a bigger pipe respectively. The liquid metal flow is divided into several streams, and every one passes through one of the ceramic pipes to form a group of electric circuits. This causes the eddy current appears in every circuit and then the resulted EMF promotes the inclusions to be eliminated out of the liquid metal. In our opinion a pipe group composed of either triangle pipes or square pipes might be much efficient[7], so instead of the circular pipes, it was decided to adopt triangle/square pipes.

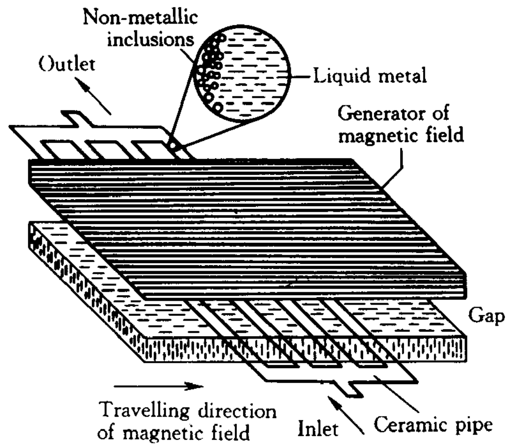

Fig.1 Schematic of equipment for purifying liquid metal by travelling magnetic field

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3 THEORY

3.1 Hypothesis

The liquid metal is supposed to be flowed in a long square or triangle pipe, as illustrated in Figs.2 and 3. The eddy current flowed along Z direction. B was set in the Y direction, and so the EMF was induced to follow along X direction. This was just the travelling direction of the magnetic field.

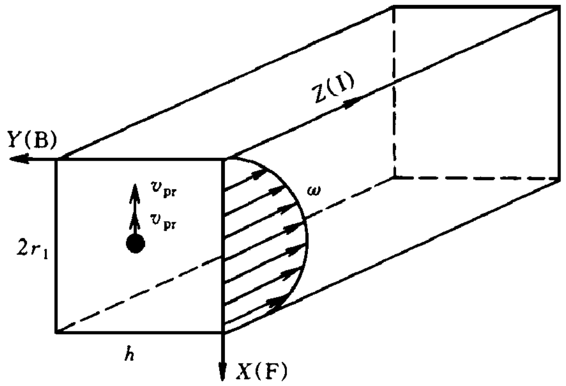

Fig.2 Distribution of flowing rate of liquid metal in a square pipe

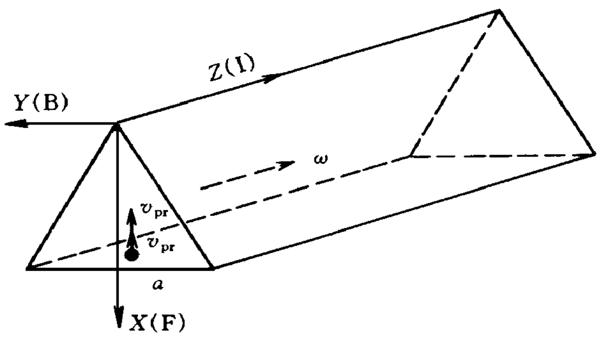

Fig.3 Schematic of triangle pipe
a —Lateral length of a triangle pipe, m

To calculate the inclusion-removal efficiency, the following hypothesis were suggested[4]:

1) The current density, the magnetic flux density (MFD) and the flowing velocity of liquid metal are stable. And the distribution of current density as well as MFD are homogeneous;

2) The inclusion particles are sphere-like and have no effect on each another;

3) The inclusion particles are very small, so the inert force can be neglected;

4) When the inclusion particles reach the pipe surface, they will adhere there;

5) EMF is perpendicular to the inner surface of the pipe.

3.2 Migrating rate of inclusion particles

The EMF acting on the liquid metal is determined as Eqn.(1):

$$F_X = B_Y \cdot J_Z \quad (J_Z = I/S) \tag{1}$$

where B_Y denotes the MFD in Y direction, J_Z denotes the current density in liquid metal in Z direction, and the same is true for the following coordinates, where the subscripts of F, B and J were omitted to simplify the expression; I is the expression of eddy current (both refer to their virtual value); S represents the section area of the pipe.

The "pinch force" can be calculated by Eqn.(2)[4]:

$$F_p = -\frac{3}{4}\frac{\pi d_p^3}{6}F = -\frac{\pi d_p^3}{8} \cdot F \tag{2}$$

where the minus expresses that its direction is opposite to that of the EMF. Considering that the pinch force will approach to the equilibrium with the viscous resistance[8] of

$$F_D = 3\pi \mu d_p V_{pr} \tag{3}$$

then the final migrating rate of the inclusion particles is related to the factors as shown by Eqn.(4):

$$V_{pr} = -d_p^2 F/24\mu \tag{4}$$

The floating rate of the inclusion particles as generally known can be calculated by Eqn.(5)[9]:

$$V_{pr} = d_p^2 \Delta \rho g/18\mu \tag{5}$$

4 THEORETICAL ANALYSIS ON INCLUSION REMOVAL EFFICIENCY

Two models were used in this paper. When the value of the ratio $d_{pipe}/L_{lateral}$ was comparably bigger, where d_{pipe} is the diameter of the pipe, and $L_{lateral}$ is the thickness of the lateral area, it could be supposed that the flowing rate of the fluid everywhere in the pipe nearly kept the same, that is to say, the flow was plug flow. When the value of the ratio $d_{pipe}/L_{lateral}$ was comparably smaller, the flowing rate of the fluid everywhere in the pipe had great difference, then the inclusion removal efficiency was related to the trajectory of the inclusion, so the trajectory model was used to calculate the efficiency.

4.1 In rectangular pipe

4.1.1 Plug flow model

Suppose the floating force and the pinch force act on the same direction (Fig.1), and metal flow in the pipes is supposed to be of the plug flow model. Then the variation of the inclusion concentration is displayed as Eqn.(6):

$$-\frac{dC}{C} = \frac{dZ \times (V_{pr} + V_{pt})}{2r_1 \bar{\omega}} \tag{6}$$

And intergating Eqn.(6), the following Eqn.(7) and Eqn.(8) can be derived:

$$C = C_0 \exp\left(-\frac{(V_{pr} + V_{pt})}{2r_1 \bar{\omega}}Z\right) \tag{7}$$

$$\eta = 1 - \frac{C}{C_0} = 1 - \exp\left(-\frac{(V_{pr} + V_{pt})}{2r_1 \bar{\omega}}Z\right) \tag{8}$$

Taking Eqns.(1), (4), (5) into account,

Eqn.(8) can be rewritten as follows:

$$\eta = 1 - \exp\left(\frac{\dfrac{d_p^2 \cdot B \cdot I}{24\mu \cdot 2r_1 \cdot h} + \dfrac{\Delta\rho g d_p^2}{18\mu}}{2r_1 \bar{\omega}} Z\right) \quad (9)$$

Fig.4 shows the relationship between the removal efficiency η of Al_2O_3 inclusions and the flowing distance of molten Al as an example.

Fig.4(a) ~ (c) show that extending the flowing distance of the liquid metal or increasing the EMF or reducing the migrating distance of the inclusions will optimize the removal efficiency. For example, to the inclusion whose diameter is 40 μm, when both magnetic flux density and current density were increased 100 %(the EMF 300 %), its removal efficiency was elevated from 45 % to 85 %, increased nearly 100 %, and if the migrating distance of the inclusions was decreased 50 %(Fig.4(c)), the removal efficiency was 87 %, which was approximately that resulted from doubling both the MFD and the current intensity. For this reason, if the first two factors can't be changed so far, then shorten the migrating distance of the inclusions will improve the removal efficiency remarkably. In practice, the ratio can be changed between the length and the width of the pipe or even use a thin pipe to shorten the migrating distance of inclusion.

It was shown in Fig.4(d) that the inclusion-removal efficiency without EMF was about 67 % lower than that with EMF in Fig.4(a). It is obvious that the TMF can increase the inclusion removal efficiency greatly.

4.1.2 Trajectory model

As known, if the flow in the circular pipe is laminar, the velocity distribution of the flow should be a parabola against the radius of the pipe. To the square pipe, the distribution of the velocity of the flow becomes a little complex. In order to simplify the calculation, it is assumed that the velocity distribution of metal flow in X-Z plane is parabolalike, and in X-Y plane it is iso-X lines(Fig.2). Thus, the following can be written:

$$\omega = \omega_m[1 - (r_1 - x)^2/r_1^2] \quad (10)$$

Assuming the migrating rate of the inclusions in Z direction is V_{pZ}, and that in X direction is V_{pX}, then V_{pZ}, V_{pX} can be written as

$$V_{pZ} = \omega_m\left[1 - \frac{(r_1 - x)^2}{r_1^2}\right] = \frac{dZ}{dX} \quad (11)$$

$$V_{pX} = V_{pr} + V_{pt} = \frac{dX}{dt} \quad (12)$$

The deduction aims to know how long the inclusions can migrate when the molten metal flows over a given distance. So divide Eqn.(11) by Eqn.(12), Eqn.(13) can be gotten

$$\frac{dZ}{dX} = \frac{V_{pZ}}{V_{pX}} = \frac{\omega_m[1 - (r_1 - x)^2/r_1^2]}{V_{pr} + V_{pt}} \quad (13)$$

Resulting from integrating Eqn.(13), the trajectory of inclusions during the metal flow process is discovered.

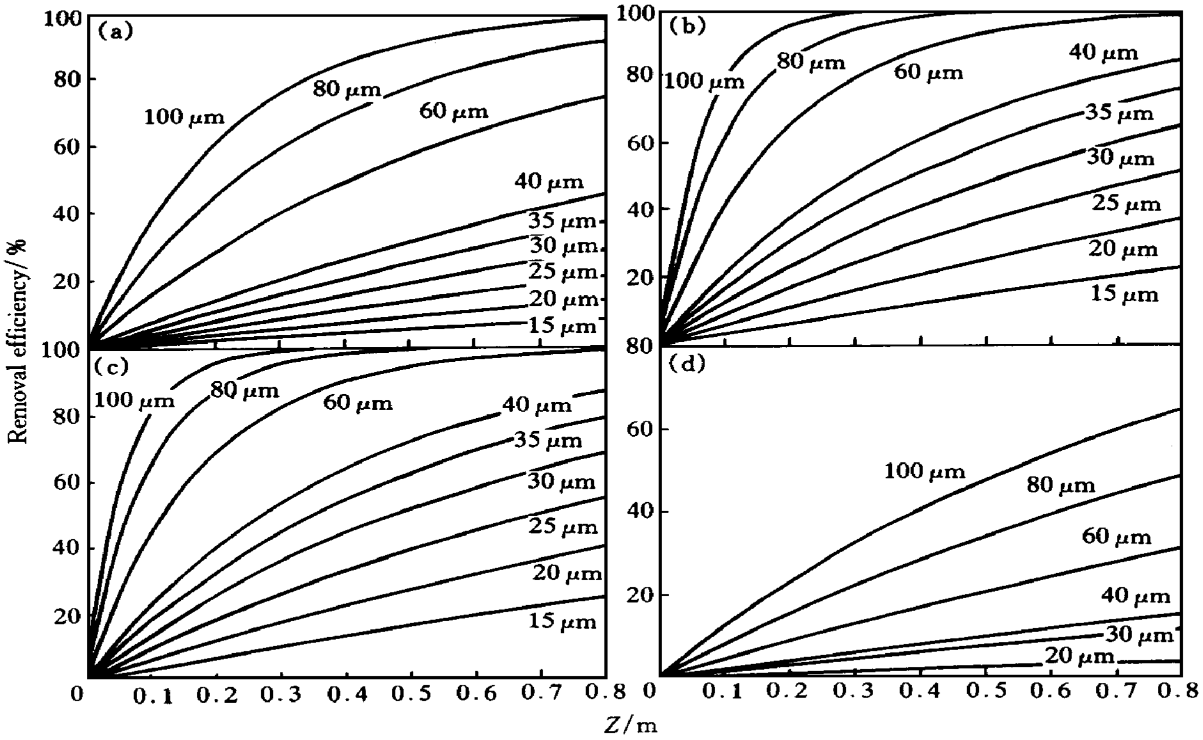

Fig.4 Calculated removal efficiency of inclusions in square pipe by using plug flow model

(a) —Data of alumna and aluminum used in calculation: $B = 0.1$ T, $I = 40$ A, $\bar{\omega} = 0.10$ m/s, $2r_1 = h = 0.01$ m, $\rho_{Al} = 2\,700$ kg/m^3, $\rho_{Al_2O_3} = 3\,900$ kg/m^3, $\mu = 0.005$ Pa·s[10]; (b) — $B = 0.2$ T, $I = 80$ A, other data are same as those in (a); (c) —$2r_1 = 0.005$ m, other data are same as those in (a); (d) — Without EMF

$$\int_0^{Z^*} dZ = \int_0^{X^*} dX \tag{14}$$

According to the trajectory, it is known that for a supposed $Z = Z^*$, $X = X^*$ reduces to zero, it means that at the initial plane $Z = 0$ all the inclusions located over the X^* can reach the pipe surface in the process of metal flow over a distance of X^*. Therefore, the removal efficiency of inclusions can be determined by Eqn.(15):

$$\eta = \frac{\int_0^X V_{pZ} \cdot h dX}{\int_0^{2r_1} V_{pZ} \cdot h dX} \tag{15}$$

According to Eqn.(11), η is obtained as

$$\eta = \frac{3}{4}\left(\frac{x^2}{r_1^2} - \frac{1}{3}\frac{x^3}{r_1^3}\right) \tag{16}$$

Assuming $Z = z/r_1$, $R = x/r_1$, then the Eqns. (13) and (16) can be written as

$$\frac{dZ}{dR} = \frac{\omega_m[1 - (1 - R)^2]}{V_{pr} + V_{pt}} = \frac{\omega_m[2R - R^2]}{V_{pr} + V_{pt}} \tag{17}$$

$$\eta = \frac{3}{4}\left(R^2 - \frac{1}{3}R^3\right) \tag{18}$$

Solve Eqns.(17), (18), the relationship between η and Z can be gotten and shown as Fig.5.

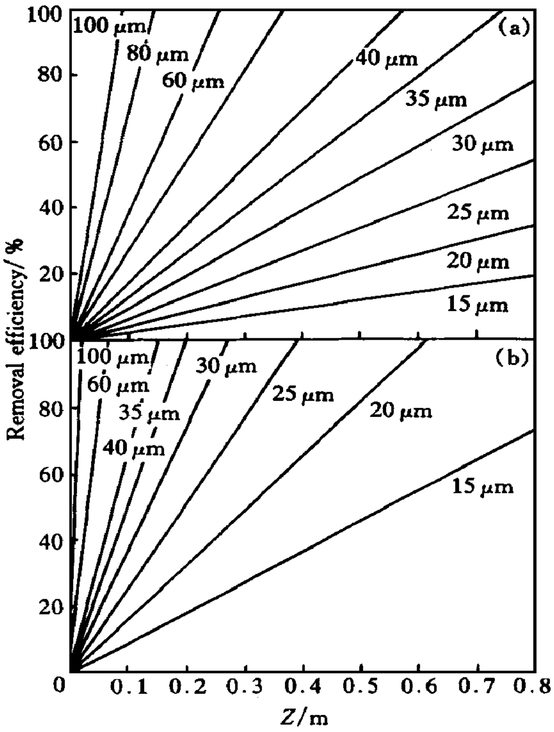

Fig.5 Calculated removal efficiency of inclusions in square pipe by using trajectory model
(a) — Maximum flowing rate is 0.2 m/s, $B = 0.2$ T, $I = 80$ A, other data are same as those in Fig.4(a); (b) — $B = 0.4$ T, $I = 160$ A, other data are same as those in Fig.5(a)

4.2 In equilateral triangle pipe

By using a triangle pipe, the turbulent due to uneven EMF acted on the liquid metal could be suppressed more efficiently[7] than by using a square pipe, for the surface area of the former pipe contacted with the liquid metal is larger than that of the latter pipe. Moreover, just in the following part, it can be seen that the inclusion removal efficiency in the triangle pipe will be higher than that in square pipe too.

4.2.1 Plug flow model

The coordinate system and the direction of the migrating rate has been shown in Fig.3. Based on Fig.3 the following relation can be obtained:

$$-\frac{dC}{C} = \frac{(V_{pr} + V_{pt})dZ}{(1/2)\cdot\sqrt{3}a/2} \tag{19}$$

The (1/2) in the denominator of the right side of Eqn.(19) is used to make the section area of a triangle pipe to be equivalent to that of a square pipe. Integrate the Eqn.(19), then

$$\eta = 1 - \exp\left(-\frac{(V_{pr} + V_{pt})}{\sqrt{3}a\bar{\omega}/4}Z\right) \tag{20}$$

Comparing Fig.6 with Fig.4, it can be known that increasing inclusion removal efficiency can be obtained by using triangle pipe instead of square one. For example, when its diameter is 40 μm, under the condition of $B = 0.2$ T, $I = 80$ A and 0.8 m of flowing distance of liquid aluminum, the inclusion removal efficiency in triangle pipe is 10 % higher than that in square pipe, further more, even without EMF, the efficiency was increased in triangle pipe too

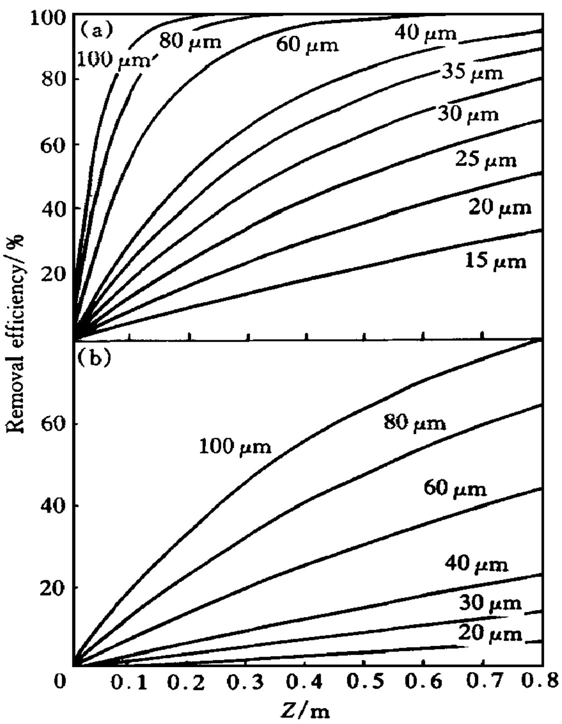

Fig.6 Calculated removal efficiency of inclusions in triangle pipe by using plug flow model
(a) — $B = 0.2$ T, $I = 80$ A, $a = 0.015$ m, other data are same as those in Fig.4(a); (b) — Without EMF

(from 25 % in Fig.4(d) to 32 % in Fig.6(b)). So, the new discovery is that when other conditions were kept the same, only selecting suitable shape of the passage of the liquid metal would increase the inclusion removal efficiency. Further more, if the inclusion removal efficiency in two kinds of pipes were equal, the necessary flowing distance of the liquid metal in triangle pipe was shorter than that in square pipe, this means that smaller area of MFD generator can be used, which saves cost in equipment.

4.2.2 Trajectory model

The velocity distribution of a laminar flow in a triangle pipe is[11]

$$\omega(y, x) = \frac{1}{2\sqrt{3}a\mu}\left(-\frac{dp^*}{dZ}\right)(x - 1/2 \cdot a\sqrt{3}) \cdot (3y^2 - x^2) \quad (21)$$

In order to simplify the calculation, assume $X = x/(\sqrt{3}a/3)$, $Y = y/(a/3)$, then Eqn.(22) is obtained:

$$\omega(y, x) = \omega_m(2X - 3)(Y^2 - X^2) \quad (22)$$

The distribution of the flowing rate in a triangle pipe is shown in Fig.7 according to Eqn.(22).

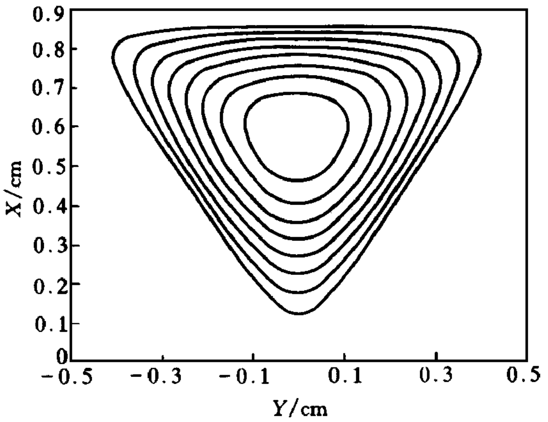

Fig.7 Distribution of flowing rate in a triangle pipe

And the V_{pZ}, V_{pX} can be written as

$$\frac{dZ}{dt} = V_{pZ} = \omega_m(2X - 3)(Y^2 - X^2) \quad (23)$$

$$-\frac{dX}{dt} = V_{pX} = V_{pr} + V_{pt} \quad (24)$$

Divide Eqn.(23) by Eqn.(24), then

$$\frac{dZ}{dX} = -\frac{\omega_m(2X - 3)(Y^2 - X^2)}{V_{pr} + V_{pt}} \quad (25)$$

The existence of the factor Y are not convenient for analysis, so integrate Eqn.(25) from $Y=0$ to $Y = x/\sqrt{3}$, then Eqn.(26) is deduced:

$$\frac{dZ}{dX} = -\frac{2a}{9}\frac{\omega_m(-2X^3 + X^2)}{V_{pr} + V_{pt}} \quad (26)$$

Integrate Eqn.(26) against X from $X=0$ to X, then

$$Z = \frac{2\sqrt{3}a}{9}\frac{\omega_m(X^3 - X^4/2)}{V_{pr} + V_{pt}} \quad (27)$$

Finally the removal efficiency of inclusions can be calculated by Eqn.(28)

$$\eta = \frac{\int_0^x dX \int_0^{\frac{x}{\sqrt{3}}} V_{pZ} dY}{\int_0^{\frac{\sqrt{3}a}{2}} dX \int_0^{\frac{x}{\sqrt{3}}} V_{pZ} dY} \quad (28)$$

According to Eqn.(23), then

$$\eta = \frac{320}{729}\left(\frac{3}{4}X^4 - \frac{1}{5}X^5\right) \quad (29)$$

Solve Eqns.(27) and (29), the relation between η and Z can be obtained, which is shown in Fig.8.

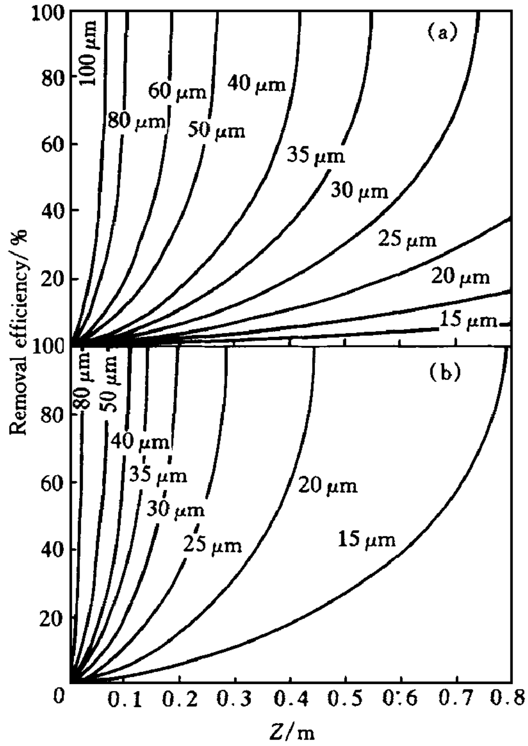

Fig.8 Calculated removal efficiency of inclusion in triangle pipe by using plug flow model
(a) — $B = 0.2$ T, $I = 80$ A, $a = 0.015$ m, other data are same as those in Fig.5(a); (b) — $B = 0.4$ T, $I = 160$ A, other data are same as those in Fig.8(a)

5 DISCUSSION

In Figs.5 and 8, it was shown that, in the case of trajectory model, increasing inclusion removal efficiency could be obtained with shorter distance of metal flow acted by EMF. This is due to the fact that, the flowing rate of the fluid changes in different position, then, with a certain distance of metal flow, the migrating time of the inclusion along the Z direction is longer than that in the case of plug flow model. According to this, the inclusion particles have sufficient time to reach the surface of the pipe, which leads to the increase in the inclusion removal efficiency.

Moreover, it is shown that the removal efficiency also depends upon the diameter of the inclusions. The bigger the diameter, the higher the removal efficiency. This is explained by Eqn.(2). The parameters as

$B = 0.4$ T and $I = 160$ A, are feasible in industry[12]. Under this condition, the inclusion whose diameter is larger than 15 μm in triangle pipe and 20 μm in square pipe will be thoroughly removed with 0.8 m of the liquid metal flowing distance. To obtain these parameters, the power of the electric source will be up to 100 kW. Suppose that 30 ceramic pipes with a length of 0.8 m were set in the TMF, and the flowing rate of the liquid aluminum was 0.1 m/s, then the electric consumption was 38 kW·h per one ton liquid aluminum, which was reasonable in industrial applications. Judging from this, the technology of purifying liquid metal using TMF is very feasible in industry.

6 CONCLUSIONS

1) The inclusion removal efficiency could be increased greatly when purifying liquid metal using travelling magnetic field, compared to that using traditional floating way by gravity.

2) The analysis by both plug flow model and trajectory model show that, the inclusion removal efficiency η can be optimized by extending the flowing distance of the liquid metal, enlarging the EMF, shortening the migrating distance of the inclusion particles and increasing the diameter of the inclusion particles. The most effective way to improve η is shortening the migrating distance of the inclusion particles, so the pipe with large ratio between length and width is more suitable to be used in this field. Increasing the EMF not only can remove inclusion particles with a smaller diameter, but also reduce the necessary area of the TMF.

3) The removal efficiency by using triangle pipe is higher than that by using square pipe. In the case of triangle pipe, for a given inclusion removal efficiency the necessary distance of metal flow is shorter than that in the case of square pipe.

4) By trajectory model, when $B = 0.4$ T and $I = 160$ A, the inclusion in liquid aluminum, whose diameter are larger than 15 μm in triangle pipe and 20 μm in square pipe will be thoroughly removed with 0.8 m of the liquid aluminum flowing distance.

The symbol definitions:

B	Magnetic flux density, T
Z	Flowing distance of the liquid metal, m
C	The content of the inclusions, %
μ	Viscosity of the liquid metal, Pa·s
C_0	The original content of the inclusions, %
V_{pr}	Velocity by pinch force, m/s
d_p	The diameter of the inclusions, m
V_{pt}	The floating velocity by gravity, m/s
F	Electromagnetic force(EMF), N/m^3
V_{pX}	The inclusion's moving velocity in X direction, m/s
F_D	Viscous resistance, N/m^3
V_{pZ}	The moving velocity of inclusion in Z direction, m/s
F_p	Pinch force, N/m^3
ω	The flowing rate in trajectory model, m/s
ω_m	Maximum flowing rate in trajectory model, m/s
I	The current in the liquid metal, A
$\overline{\omega}$	Flowing rate in plug flow model, m/s
p^*	Pressure, Pa
η	Removal efficiency of inclusions, %
S	The section area of the pipe, m^2

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