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Materials

Study on the breakup length of circular impinging jet

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Abstract: Circular impinging jet, which is widely used in accelerated control cooling (ACC) equipment to accelerate the cooling of hot rolled plates, is subject to breakup, and may result in undesirable cooling effect. Therefore, the jet breakup should be avoided as possible in industrial production. The objective of this study is to find the relation of the processing parameters of the ACC equipment *versus* the breakup length of jet with weaker turbulence. To obtain quantitative findings, not only relative experimental study but also numerical simulation was carried out. For a weaker turbulent water jet, the breakup length increases with the increase of jet diameter, as well as with the jet velocity; jet diameter has a significant effect on the breakup length for a certain flow rate when compared with jet velocity; finally a suggested correlation of the jet breakup length *versus* jet Weber number is presented in this study.

Key words: hot rolled plate; circular impinging jet; breakup length; numerical simulation

1. Introduction

Impinging jet is a flow state that is widely prevalent in nature, such as the flow escaping from a water tap system, the fall of waterfall from a high mountain, and so on. With the characteristic of high-efficiency heat transfer, impinging jet has been widely used to cool the high temperature products in modern industrial production. For example, air impinging jet can be used to cool high temperature electronic elements in electronic industry; water impinging jet can be used to accelerate the cooling of steel plates in the steel rolling process to achieve better mechanical properties and to improve productivity; likewise, impinging jet cooling had been widely used in nuclear industry and glass industry for a long time. However, just like the jet breakup of a tap water stream, jet breakup phenomenon is possible after the liquid impinging jet exited from the ACC equipment had passed a certain distance (Fig. 1). Jet breakup will inevitably result in the interrupted flow and discontinuous cooling effect, and consequently it will cause a undesired thermal field profile in the plate. Therefore, jet breakup should be eliminated as possible when commissioning the ACC equipment. From this standpoint, it is necessary to discover the relation of the breakup length (distance from jet exit to breakup point) of jet *versus* the processing parameters of the ACC equipment, such as jet diameter and jet velocity. The breakup length of the impinging jet with weaker turbulence will be experimentally and numerically discussed in this study.

Fig. 1. Breakup scene of impinging jet.

2. Overview of previous study

Since the 19th century, investigators have made a great deal of relative studies, which is partly attributed to the fact that the breakup of jet is a classic hydrodynamic phenomenon and partly to the fact that the study of the phenomenon has important practical significance. The earlier study can be traced back to the work of Lord Rayleigh [1], he gave a linear solution correlation, which can be used to compute jet breakup length, however, the results given by this correlation has a considerable deviation when compared with the experimental results. On the basis of the linearity theory of Rayleigh and by considering the viscosity of ambient gas, Weber [2] had reported a corrected correlation that can be used to compute jet breakup length. In Rayleigh's linear limit, the circular jet is unstable because of a natural growth of axisymmetric disturbances. The growth rate of disturbance depends on the

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jet radius and liquid properties, whereas the wavelength of the most rapidly growing disturbance λ_R is a simple function of the jet radius r_j only (Bogy [3]). From several experimental observations (Crane *et al.* [4]; Donnelly and Glaberson [5]; Goedde and Yuen [6]), it is well known that the breakup of jet differs from the linear description in several ways. Yarin [7] had summarized the work of anterior investigators and considered that the capillarity closely related to the surface tension is the cause of jet breakup. Recently, some authors (Wu *et al.* [8-9], Dai *et al.* [10], Kowalewski [11], Kerst *et al.* [12]) and their associates performed experiments to investigate the turbulent primary breakup. It was noteworthy that in the study of Sallam *et al.* [13], jet breakup was classified into three cases, and corresponding correlations were given depending on the turbulence scale of jet. They considered that the jet with weak turbulence will breakup when the turbulent amplitude of jet surface makes enough effect on the axial line of jet; the major factor of the jet breakup with high turbulence is the interaction effect between jet flow and ambient atmosphere.

3. Experimental equipment

The experimental study was carried out to quantitatively investigate the breakup length, and the principle diagram of the experimental equipment is shown in Fig. 2. The purpose of the pump A is to lift water to the water box C; the air bag B is used to eliminate the pulse of water pressure, so that water jet can exit from the nozzle E *via* the flow control valve D. Various flow states of jet can be realized by adjusting the opening of the flow control valve D. The breakup length of jet flow can be measured with rule F; the function of the water collecting tank G is to collect jet water to construct a closed water circulating system.

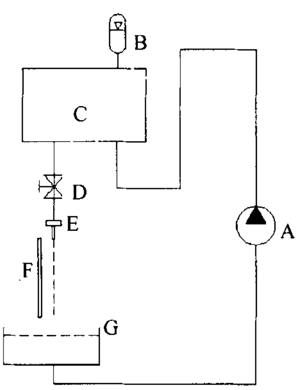

Fig. 2. Principle diagram of the experiment.

4. Numerical simulation

4.1. Mathematical model

Water circular impinging jet moving in atmosphere can be described with a two-dimensional axisymmetric model. The computation domain is shown in Fig. 3, in which OE indicates the symmetric axis, O-A-B-C-D-E indicates the enclosed solution domain, and OA indicates the jet inlet. To make the computation convenient, the model could be simplified in accordance with the following reasonable rules: (1) water jet flow can be taken as a stable axisymmetric stream, and the ambient gas is still atmosphere; (2) water is considered as an incompressible media; (3) jet flow has a uniform exit velocity profile.

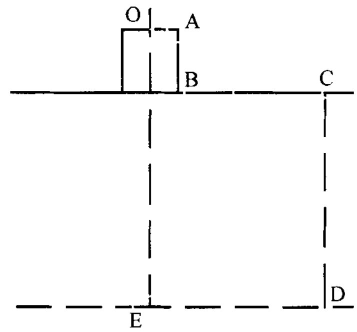

Fig. 3. Diagram of the solution domain.

4.2. Control equation

In a cylindrical coordination system, the mass equation of impinging jet can be expressed as:

$$\frac{1}{r}\left(\frac{\partial(ru)}{\partial r}\right)+\frac{\partial w}{\partial z}=0 \qquad (1)$$

The N-S equation of radial direction can be denoted as:

$$u\frac{\partial u}{\partial r}+w\frac{\partial u}{\partial z}=-\frac{\partial p}{\partial r}+\frac{1}{Re}\left(\nabla^2 u-\frac{u^2}{r}\right) \qquad (2)$$

The N-S equation of axial direction can be denoted as:

$$u\frac{\partial w}{\partial r}+w\frac{\partial w}{\partial z}=-\frac{\partial p}{\partial z}+\frac{1}{Re}\left(\nabla^2 w\right) \qquad (3)$$

where r is the radial direction position, z the axial direction position, u the velocity component in radial direction, w the velocity component in axial direction, p the pressure, and Re the Reynolds number. As a considerable affecting factor, the acceleration of gravity g=9.81 m^2/s is available.

4.3. Boundary condition

In Fig. 3, OA denotes the jet inlet with boundary condition w=constant, $u=0$, and $p=p_\infty$; AB denotes the non-slip wall; BC, CD, and DE are the pressure outlets with $p=p_\infty$, p_∞ is the atmosphere pressure, 1.01×10^5 Pa; OE is the symmetric axis with $u=0$.