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Influence of secondary droplet on separation performance of wave-type vane separator

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Abstract. The steam-water separator is a vital device of the steam generator in nuclear power plant. Its separation performance greatly influences the efficiency, safety and reliability of the power station. When the droplet moves in separator, the droplet can collide with the separator wall, and the secondary droplets may generate when the collision velocity of the primary droplet is sufficiently large. To investigate the effect of secondary droplet on separation performance of the separator, the simulation is conducted using droplet motion model and generation model of secondary droplet. The trajectories of both primary droplet and secondary droplet are presented. The effect of the secondary droplet on the separator separation efficiency is analyzed. The results can guide the design of the separator, where both of the droplet motion and the secondary droplets generation need to be considered.

1. Introduction
The steam-water separator is an important part of the steam generator. When the droplet moves in separator, the droplet may collide with the wall, and secondary droplets may generate when collision velocity of primary droplet is sufficiently large. The secondary droplet may have an effect on separation efficiency. Therefore, it is important to study the behavior of secondary droplet.

There are a lot of studies about the separation performance. Prabhudharwadkar *et al* [1] studied the water carryover of separator drum. Li *et al* [2] studied the wave plate separator efficiency. Nakao *et al* [3,4] studied the separating efficiency of the wave-plate separator. Galletti *et al* [5] simulated the separating efficiency of the wave-plate eliminator. However, there are few studies about the separating mechanism [6-8]. The authors' research team has also studied the separating mechanism from the droplet behavior, including droplet generation [9], droplet moving [10], droplet-droplet collision [11-13], droplet phase change [14-16], secondary droplets generation [17], and so on. Zhao *et al* [14] analyzed the effects of the droplet evaporation on the efficiency of the separator and revealed that this effect could be neglected. Zhao *et al* [15] obtained the separation efficiency and pressure drop of the whole AP1000 steam-water separator using the Euler-Lagrange based on the three-dimensional geometry model. Zhang *et al* [18] simulated the separation performance of the wave-type vane separator and proposed the design structure with higher separating efficiency. Zhang and Bo [19] numerically studied the binary-droplet collision process in the separator and divided the collision regime into four types. They also analyzed the droplet collision characteristics by the Monte Carlo methods [20]. In addition, Li *et al* [21] compared different turbulence models used in the simulation of the corrugated plate separator and pointed out that the large eddy simulation model was more precise. Yang *et al* [22] studied the separating efficiency of the separator using the population balance model and analyzed the effects of the droplet sizes on the efficiency. Xiao *et al* [23] experimentally studied the effects of the collection hooks on the separation efficiency and presented the critical velocity. Li *et al* [24] pointed out that the performance of the separator with double hooks was biggest by experimental analysis.

However, studies about the secondary droplets behavior in the separator are few. Nakao *et al* [7] found that there are small droplets in the outlet of the wave-type vane separator which do not exist at the inlet, and pointed out three kinds of reasons of the fine droplets generation: the breakup of droplet, breakup of liquid film, droplet impingement on liquid film. Wang *et al* [25] analyzed the generation mechanism of the secondary droplets in the separator and pointed that the shear flow and the droplet colliding with the film were two main reasons. Cossali *et al* [26] investigated the droplet impingement process on the film. Samenfink *et al* [27] investigated effect of the droplet on the shear film. Li *et al* [2] pointed that the droplet colliding with the film was a very important mechanism.

Though there are some investigations about the secondary droplet, the effect of secondary droplet on separating performance is not clear. In addition, the previous investigations just consider the whole secondary droplets as an integral. Therefore, it is necessary to figure out the detailed effects of each kinds of the secondary droplet on the separation efficiency, which is vitally important to the design of the separator.

The present paper investigates the effect of the secondary droplet (generated by the primary droplet impinging on the wet surface of the separator) on the separating efficiency of the wave-plate separator. Simulation of the separating performance is conducted, using droplet motion model and the generation model of secondary droplet. Trajectories of both primary droplet and secondary droplet are presented. The effect of secondary droplet on separating efficiency is analyzed.

2. Simulation method

In the separator, the force schematic of the droplet is shown in figure 1.

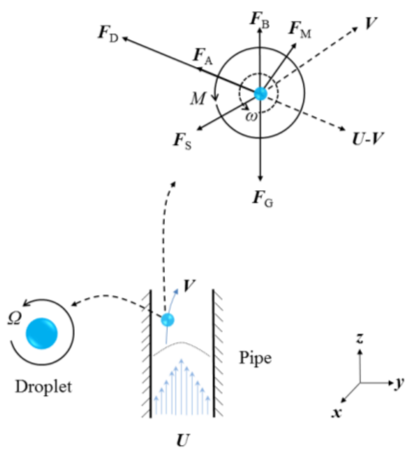

Figure 1. Force schematic of the droplets [14].

In figure 1, $\boldsymbol{F}_{\mathrm{D}}$ is flow drag force; $\boldsymbol{F}_{\mathrm{A}}$ is additional mass force; $\boldsymbol{F}_{\mathrm{V}}$ is the volume force, including the gravity and buoyancy; $\boldsymbol{F}_{\mathrm{M}}$ is Magnus lift force; $\boldsymbol{F}_{\mathrm{S}}$ is Saffman lift force.

The governing equations of droplet motion model include the droplet displacement $\boldsymbol{x}(t)$ equation, rotation equation $\boldsymbol{\omega}(t)$ and translation velocity $\boldsymbol{v}(t)$ equation. The equation set is simplified and is as follows:

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$$\begin{cases} \dfrac{\mathrm{d}\boldsymbol{x}}{\mathrm{d}t} = \boldsymbol{v}, \\ \dfrac{\mathrm{d}\boldsymbol{\omega}}{\mathrm{d}t} = \lambda_1 C_{\mathrm{M}} \left|\boldsymbol{\omega} - \dfrac{\boldsymbol{\Omega}}{2}\right| (\boldsymbol{\omega} - \dfrac{\boldsymbol{\Omega}}{2}), \\ \dfrac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} = \lambda_2 C_{\mathrm{D}} \left|\boldsymbol{u}-\boldsymbol{v}\right| (\boldsymbol{u}-\boldsymbol{v}) + \lambda_3 C_{\mathrm{Ma}} (\boldsymbol{u}-\boldsymbol{v}) \times (\boldsymbol{\omega} - \dfrac{\boldsymbol{\Omega}}{2}) + \\ \qquad \lambda_4 C_{\mathrm{Sa}} \left|\boldsymbol{\Omega}\right|^{-0.5} [(\boldsymbol{u}-\boldsymbol{v}) \times \boldsymbol{\Omega}] + \lambda_5 \boldsymbol{g}. \end{cases}$$

Here, C_{M}, C_{D}, C_{Ma}, C_{Sa} are the coefficients of the according force and force moment, respectively. λ_1, λ_2, λ_3, λ_4, λ_5 are the normalization coefficients. The detailed expressions can refer to references [14,15].

The Euler-Lagrange method is used to simulate the droplet motion and separation in the separator, where the Euler method is used to obtain the vapor flow field by the software of FLUENT 16.0, and the droplet motion model is solved using Lagrange method by C++ programs. Due to the typical form of $y'=f(x,y)$ of the upper equation set, the four steps Runge-Kutta method is used. The detailed approach and numerical validation can refer to references [14-16].

3. Results analysis

3.1. Generation condition of secondary droplet in wave-plate separator

During the course of the operation of wave-type vane separator, the plate of the separator is usually covered by the water film resulting from the droplet collision with the plate, which is the typical wetted surface. When the inlet droplet (primary droplet) moves in the wave-plate separator, it may collide with wetted surface. However, only the droplets with sufficiently large normal velocity or with considerably large diameters, can satisfy the critical criterion beyond which the secondary droplet will generate when the inlet droplet collides with the wetted surface. In order to figure out the generation condition of secondary droplet in the separator, the analysis about the generation of secondary droplet is conducted according to the operation condition of the wave-type vane separator as follows.

The criterion number of K is put forward to determine whether the droplet splashing occurs or not [28]. The criterion number of K is defined as $K=WeOh^{-0.4}$. Here We is weber number; Oh is Ohnesorge number. The expressions of We, Oh and Reynolds number are presented as follows:

$$We = \frac{\rho U^2 d}{\sigma} \quad Oh = \frac{We^{0.5}}{Re} \quad Re = \frac{\rho U d}{\mu}$$

Here, ρ, σ, μ are the droplet density, surface tension, dynamic viscosity, respectively. d is droplet diameter. U is normal velocity of droplet colliding with the wall of the separator.

When the criterion number of K of the inlet droplet is beyond the critical one, the liquid crown will generate, the liquid jets form at the edge of the crown, the droplet splashing will take place, and the secondary droplets generate, as presented in figure 2.

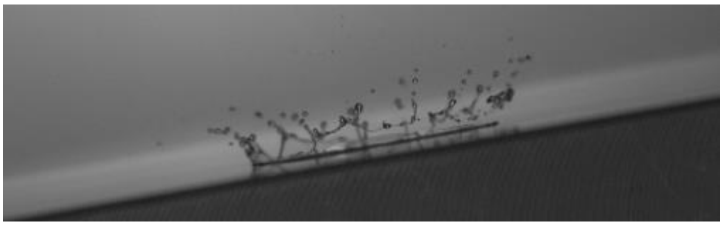

Figure 2. Droplet splashing phenomena when impacting wetted surface [29] (d=2.47 mm, U=2.9 m/s, α=10°).

The critical criterion number of K for the generation of secondary droplet over relative thickness of the water film is shown in figure 3, based on large quantities of experiments. Here, $H^*=h/d$ is dimensionless thickness of water film, and h is initial liquid film thickness. As presented in figure 3, the critical criterion number of K decreases with the dimensionless thickness of water film within the range of $0.005< H^*<0.035$. And if criterion number of K of inlet droplet is beyond critical one, secondary droplets will generate.

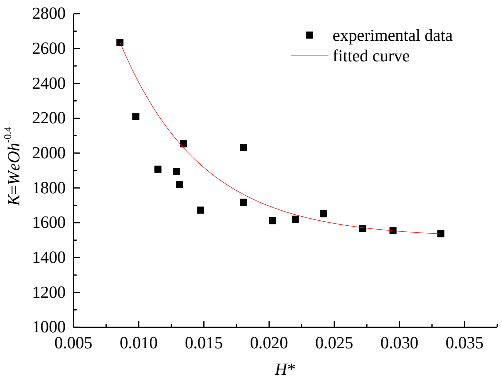

Figure 3. Critical criterion number of K over dimensionless thickness of water film.

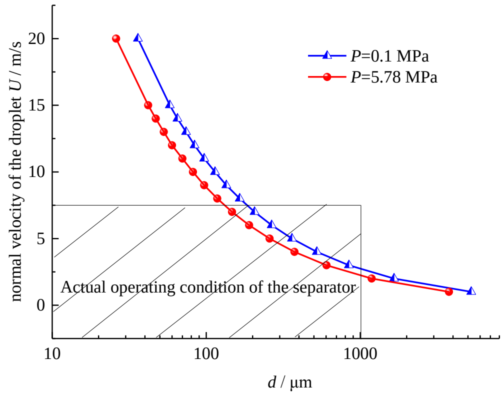

Figure 4. Generation map of secondary droplet under pressure of 0.101325 MPa and 5.78 MPa.

The diameter of the droplet in the separator is usually within range of 2 μm<d<1 mm and the inlet velocity of the wave-plate separator is 1~6 m/s approximately. Here, in order to obtain generation map of the secondary droplet at wider ranges, the parameters investigated in this paper are extended to 2 μm<d<1 mm and velocity between 1~20 m/s. The fluid in the separator is water steam. The generation maps of the secondary droplet under the condition of both the atmosphere pressure (0.101325 MPa) and the operation pressure of AP1000 steam-water separator (5.78 MPa) [15] are presented in figure 4, according to the curve of the critical criterion number of K as shown in figure 3. It should be pointed that the shadow area in figure 4 is the actual operating condition of the separator. Only when the parameters of those conditions locate in the upper right of the critical curve, the secondary droplet will generate.

Figure 4 indicates that only the droplets with sufficiently large normal velocity or with considerably large diameters, can satisfy the critical criterion beyond which the secondary droplet will generate when the inlet droplet collides with the wetted surface. When the droplet diameter is small, the colliding velocity must be larger; when the colliding velocity is slow, the droplet should be bigger. The colliding velocity must be larger than 8~9 m/s for the droplet with diameter of 100 μm as presented in figure 4, which agrees well with experimental results of Wang *et al* [30] and Li *et al* [2] They point that only when inlet velocity is beyond 6.7 m/s approximately, the secondary will generate in the wave-plate separator. Furthermore, only when the droplet diameter is larger than 605 μm for the colliding normal velocity of 3 m/s the secondary will generate as shown in figure 4.

Besides, figure 4 reveals that the critical curve of the pressure of 0.101325 MPa is beyond that of 5.78 MPa, which implies that it is more likely to generate the secondary droplet with the increasing operation pressure. That is mainly because with the pressure increase, the density and surface tension of the droplet decrease rapidly, which results in the decreasing of the criterion number of K. in addition, the droplet is more difficult to remain spherical due to the reduced surface tension. Furthermore, most of the shadow area (the actual operating condition of the wave-type vane separator) is below critical criterion curve as shown in figure 4, which indicates that it will not generate the secondary droplet for most of the inlet droplets under the normal operating condition of separator.

3.2. Effect of secondary droplet on separating efficiency

To obtain the detailed parameters of the secondary droplet generating in the wave-plate separator and verify the above analysis, the simulation of the separation performance of the wave-type vane separator is conducted, using droplet motion model and generation model of secondary droplets. The trajectories of both the primary droplet and secondary droplet are presented. The effect of the secondary droplet on efficiency of the separator is analyzed as well.

The numerical conditions are selected as the working condition of AP1000 separator and are as follows: the operation pressure is 5.78 MPa, the fluid is water steam. The inlet droplet diameter is 500 μm; the inlet velocity is 6 m/s. The inlet droplets are divided into 8 groups uniformly according to the position of the inlet of wave-plate separator. The structure of the wave-plate separator is presented in figures 5 and 6. The length of one plate is 25 mm and the angle of inclination is 45°. The space between two plates is 8.3 mm. The numerical steam velocity and pressure contours in the wave-plate are presented in figure 5.

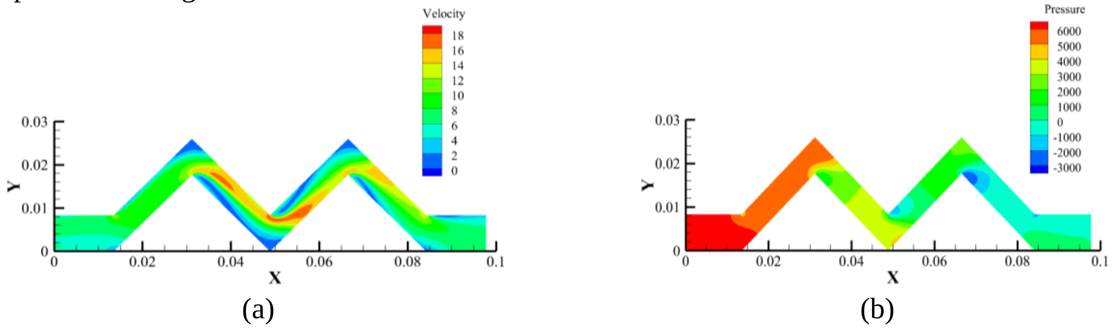

Figure 5. Velocity and pressure contours of wave-type vane separator (5.78 MPa, U=6 m/s). (a) Velocity contours and (b) Pressure contour.

The trajectories of the primary input droplet are shown in figure 6. Figure 6 reveals that all the primary droplets collide with the front surface of the separator. That is mainly because the diameter of the primary droplet is relatively large, the inertia of the droplet is big as well, and the droplet is not easy to change the motion direction when moving in the separator, which leads to the collision with the surface of the separator.

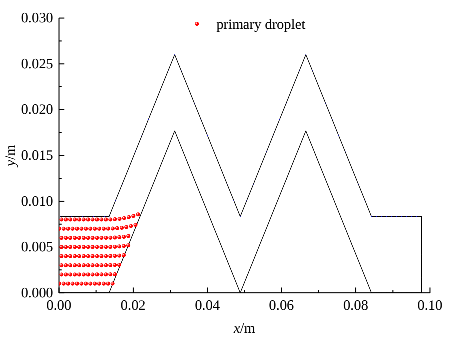

Figure 6. Trajectories of primary droplets.

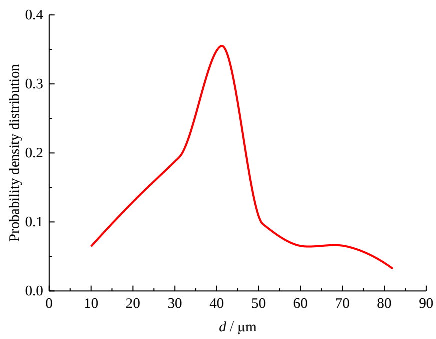

Figure 7. Diameter distribution of secondary droplets.

According to the generation model of the secondary droplet and the experimental results [29], the probability density distribution of the diameter of secondary droplets is presented in figure 7. Figure 7 indicates that the distribution is Gaussian distribution approximately. The diameters of the generated secondary droplets are between 10~82 μm. The average number of the secondary droplets resulting from one primary droplet splashing when colliding with the wetted surface (water film) is about 11~15.

The newly generated secondary droplets will continue moving in the wave-plate separator carried over by the steam flow, until escaping from the separator or colliding with the vane surface again.

When the secondary droplet collides with the vane surface, it may adhere to the surface or lead to the additional secondary droplets generation when the velocity is large enough. The trajectories of the secondary droplets and the total droplets are presented in figures 8(a) and 8(b), respectively. Figure 8(a) indicates that the secondary droplets generate above the position the droplets colliding with the surface, and are carried over by the steam. All the secondary droplets colliding with wetted vane surface adhere to the surface. Only the secondary droplets with the diameter of 10~12 μm may move out of the separator, and the other secondary droplets adhere to the surface. That is because the diameters of the secondary droplets are relatively small, and the kinetic energy of the secondary droplets is not large enough to provide the energy above which the droplet splashing can generate at the local velocity. The droplets with smaller diameters are more easily to move with the steam flow and are more likely to move out of the separator. The larger droplets are more difficult to change the motion direction due to the larger inertia, consequently colliding with the wall surface. In addition, figure 8 reveals that the secondary droplets change the droplet trajectories obviously. Though there are only a small part of secondary droplets can escape the separator, figure 8 can provide basis for the installation of the drain tank, and more drain tanks should be installed around the two bends in front of the separator.

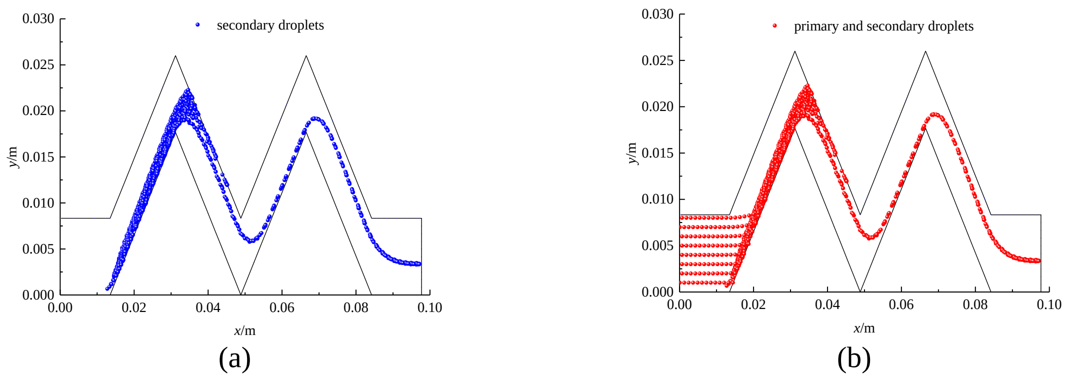

Figure 8. Influence of secondary droplets on the droplet trajectories. (a) Secondary droplets and (b) Primary droplets.

Table 1. Influence of secondary droplets on the separation efficiency of the separator.

Mass fraction of secondary droplets	Separation efficiency without secondary droplets	Separation efficiency with secondary droplets
1.4%	100%	99.986%

Table 1 presents mass fraction of secondary droplets and the influence of secondary droplets on the separation efficiency of the separator. As shown in table 1, the mass fraction of secondary droplets is 1.4% according to the statistical calculation. The efficiency for the input droplets with diameter of 500 μm is 100 % when neglecting the secondary droplets. However, the separation efficiency reduces to 99.986 % when considering the effect of secondary droplets, due to 0.014 % of the droplet escaping from the separator. As the difference is sufficiently small, the influence can be neglected under the actual operation conditions considering the experimental and numerical discrepancies. Therefore, the effect of secondary droplets generation mechanism resulting from the primary droplets colliding with wetted surface on the separation efficiency can be neglected. There are mainly two reasons: (1) The mass of secondary droplets is small comparing to the input primary droplets: Firstly, the liquid crown will generate; then, the liquid jets form at the edge of the crown; then, the droplet splashing will take place; finally, the secondary droplets generate. Consequently, the mass of secondary droplets is less than 5% of that of the primary droplet. (2) The value of K is less than that of the critical one, and it will not generate the secondary droplet for most of the inlet droplet, under the normal operating condition of the wave-plate separator.

Furthermore, there are mainly three mechanisms of the generation of the secondary droplets: the breakup of droplet, breakup of the liquid film, droplet impact on the film [7]. According to the investigation of this paper, the mechanism of droplet impingement on the film is not the main reason and can be neglected. However, the liquid crown and column will generate after the droplet collides with liquid film. The liquid crown and column are more easily broken by the shear steam flow, which may increase the generation of the secondary droplets. The other two mechanisms should be studied in the future investigations in detail.

4. Conclusions

The present paper investigated the influence of the secondary droplet (generated by the primary droplet impinging on the wet surface of the separator) on the separating performance of the wave-type vane separator. The simulation of the separation performance of the wave-type vane separator is conducted by droplet motion model and secondary droplets generation model. The trajectories of both primary droplet and secondary droplet are presented. The effect of secondary droplet on the separating efficiency of the wave-type vane separator is analyzed. Conclusions have been made as follows.

- The generation maps of the secondary droplet under the condition of both the pressure of 0.101325 MPa and the operation pressure of AP1000 steam-water separator of 5.78 MPa are presented. The generation of the secondary droplet can be forecasted according to the map.
- It is more likely to generate the secondary droplets with the increasing operation pressure. It will not generate the secondary droplets for most of the inlet droplets under the normal operating condition of wave-type vane separator.
- The mass fraction of the secondary droplets is 1.4%. The secondary droplets can lead to 0.014 % decrease of the separation efficiency of the wave-type vane separator for input droplets with the diameter of 500 μm.

The present approach can numerically estimate the influence of the secondary droplet on the separation efficiency. The results can guide the design of the separator, where both of the droplet motion and the secondary droplets generation need to be considered, especially when the velocity is large.

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