EFFECTS OF SERRATED PULSATING AIRFLOW ON LIQUID FILM EVAPORATION IN A VERTICAL CHANNEL: A NUMERICAL STUDY

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ABSTRACT

Effects of serrated pulsating airflow on liquid film evaporation in a falling film channel was numerically studied based on a two-dimensional model. The mechanism of pulsating airflow evaporation was studied as the pulsating airflow swept across the vertical liquid film surface at the stagnant temperature. Effects of amplitude, frequency, and velocity of the serrated pulsating airflow at certain evaporation time on evaporation were analyzed. Compared with the uniform airflow, the highest relative evaporation of liquid film on vertical pipe inner surface was increased by about 0.3%. When the airflow was pulsating, the cycle of vapor mass flow rate was the same as the cycle of pulsating airflow. Pulsating airflow disturbed the boundary layer periodically and carried the vapor away; this intensified the mass transfer of liquid film, hence promoting vapor generation under certain conditions.

Keywords: numerical simulation; serrated pulsating airflow; water evaporation; liquid film surface

1. INTRODUCTION

The rapidly increasing demand for fresh water is triggering severe water crisis globally. The global water storage is about 1.386 billion cubic kilometers, and only account for 0.2% of global water storage is available. Eighty countries and regions with a population of about 1.5 billion lack fresh water, and about 300 million of them fall in to the trap of water shortage. It is estimated that 3 billion people in the world will face water shortage in 2025, and 40 countries will be seriously deficient in fresh water (Gao and Ruan, 2015). With the increasing problems of water resource reduction and water pollution, the water crisis has become the world's second environmental issue after the global warming. Desalination is an inevitable choice to solve the water crisis and develop new safe water sources (Wang and Zhou et al., 2003). Multi-effect evaporation, multi-stage flashing, vapor compression distillation, solar distillation, crystallization, electro-dialysis and reverse osmosis methods are the techniques of desalinations (Choi and Yoon, 2019). Some new technologies for seawater desalination have been developed to facilitate water evaporation (Xie and Li et al, 2019).

Pulsating flows occurred in various technical systems and engineering applications (Srivastava and Dhiman, 2019; Zhai and Wang et al, 2015; Huang and Yang et al, 2010). Piston pumps, compressors, resonance tube vibrations, flow control valves, flow separation phenomena behind obstacles in pipelines, and some multiphase flow conditions present in the industry generally promote the occurrence of pulsating and other dynamic changes in fluid flow parameters. Pulsating can find its applications in many industries, such as energy, automotive, chemical, pharmaceutical, and food industry (Douglas and Gasior et al, 1995). Many studies about the use of pulsating energy have been carried out.

Golstman and Saushin (2019) designed a pulsator based on the different frequencies to obtain a continuous pulsating flow that could provide sinusoidal fluctuations in a channel. Kærn and Markussen et al (2018) compared the liquid mass flow and vapor quality of the pulsating and non-pulsating flow in a tube with different periods through the experiments of uniform and pulsating boiling in the tube. They concluded that pulsating flow evaporation efficiency was higher than that without pulsating evaporation in a certain period. Teng and Lim et al (2018) investigated heat transfer from an immersed tube in a pulsating fluidized bed and obtained the effects of immersed tube’s temperature, pulsating frequency, inlet superficial velocity and pulsating amplitude on heat transfer behaviors; they observed the best heat transfer performance at high pulsating frequency. Yang and Zhang et al (2018) studied a two-phase pulsating flow in the evaporator. By measuring the heat transfer coefficient of pulsating two-phase flow of R134a in an evaporation channel, it was concluded that the convective heat transfer efficiency of pulsating airflow was higher than that of the non-pulsating airflow in a certain period.

Zhai and Dong et al (2009) simulated the turbulent pulsating flow and heat transfer using the standard k-ε model combined with the experimental parameters of pulsating burner tailpipe, and established a turbulent flow calculation model that was suitable for the pulsating flow under experimental conditions. They found that pulsating had effects on heat transfer coefficient and friction coefficient by studying the effects of pressure, amplitude and frequency on turbulent flow and heat transfer characteristics in turbulent flow. Li and Guo et al (2019) investigated the slot-jet impingement and revealed that triangular wave could achieve high-efficient heat transfer enhancement. Leonard and Lim et al (2019) experimentally studied the mixing and segregation behaviors of a binary mixture in a pulsating fluidized bed by applying a square-wave pulsating flow. The result showed that magnitudes of particle velocity were high at large pulsating amplitudes or high pulsating frequencies. Wu and Wang (2007) researched the turbulent pulsating flow and heat transfer in an internally longitudinal protuberant finned tube. They found that the intensity of heat transfer enhancement increased with increase of pulsating frequency, while the pressure drop was simultaneously increased. The intensification of heat transfer in
internally longitudinal protuberant finned tube was more significant than the pressure drop with increase of pulsating frequency.

In terms of enhanced heat transfer, the pulsating working medium can intensify the perturbance to the boundary layer, thereby enhancing the convective heat transfer between the fluids (Li and Xiang et al, 2012; Feng and Guo et al, 1998). It was found that the water evaporation rate increased by 1.5 times if the airflow was pulsating compared with the uniform airflow at the certain condition (Liu, 2001). Based on these studies, the perturbance had a certain effect on evaporation. By utilizing the perturbance, the higher the evaporation efficiency. Authors (Zhong and Ling et al, 2020) established a two-dimensional physical and mathematical model of vertical plate falling film evaporation, and studied the effects of pulsating airflow on falling film evaporation process at vertical plate. We found compared with uniform airflow, the pulsating airflow can effectively enhance the convective mass transfer of falling film evaporation. So we use the same idea and method research the effects of serrated pulsating airflow on falling film airflow evaporation process on the inner surface of the vertical round channel.

The objective of this work is to study evaporation of a vertical liquid film surface perturbed by serrated pulsating airflow to enhance the water evaporation. To analyze the effects of the flow parameters of serrated pulsating airflow on evaporation, water evaporation as the pulsating airflow sweeping through the vertical water surface at stagnation temperature will be studied. Effects of amplitude, frequency and airflow velocity of serrated pulsating airflow on the water evaporation will be investigated.

2. THEORETICAL MODEL

2.1 Physical model

![Fig. 1 Physical model](image)

Fig.1 shows a simplified two-dimensional model of a serrated pulsating airflow sweeping through the liquid film in a falling film channel. The water forms a liquid film flowing downward on the inner surface of the channel. The pulsating airflow enters into the top of the channel, sweeping through the liquid film surface for heat exchange, and carries the vapor away from the bottom of the channel. The geometry parameters in the physical model are set as \(H=0.5\) m, \(D=0.05\) m, and \(\delta=0.002\) m.

2.2 Mathematical models

2.2.1 Governing equations

Volume of fluid (VOF) model can simulate two or more non-mixed fluids, and it is more suitable for simulations with large variations in gas-liquid interface (Gao and Morley et al, 2003; Vivekanand and Rajul 2019; Kihara, and Obata et al, 2019). Comparing with the standard \(k-\varepsilon\) model, the RNG \(k-\varepsilon\) model is derived from the instantaneous Navier-Stokes equations. It can handle high strain rate and streamline bending flow, capturing turbulent diffusion at multiple scales which is suitable to model flow near the wall and is more reliable than the standard \(k-\varepsilon\) model (Chen, 2018; Han and Wang et al, 2010; Yakhout and Orszag, 1986). This work solves the two-dimensional unsteady incompressible flow and heat transfer through RNG \(k-\varepsilon\) model and VOF multi-phases method. The governing equations are as follows. The rates of evaporation condensation are given by (Lee, 1980):

\[
\begin{align*}
\frac{\partial u_w}{\partial x} + \frac{\partial v_w}{\partial y} &= 0 \\
\frac{\partial u_w}{\partial x} + \frac{\partial v_w}{\partial y} &= 0
\end{align*}
\]

where \(u_w\) is axial velocity, \(v_w\) is radial velocity of the water film.

Momentum equation of water film is:

\[
\rho_w \left( u_w \frac{\partial u_w}{\partial x} + v_w \frac{\partial u_w}{\partial y} \right) = -\frac{\partial p_w}{\partial x} + \eta_0 \left( \frac{\partial u_w}{\partial x} + \frac{\partial u_w}{\partial x} \right) + \rho_w g
\]

where \(\eta_0\) is the dynamic viscosity and \(g\) is gravitational acceleration.

Energy equation of mixture film (vapor and air) is as following:

\[
\begin{align*}
\frac{\partial}{\partial x} \left( \rho C_{p,m} T_w \right) &= \frac{\partial}{\partial y} \left( \rho C_{p,m} T_w \right) = \frac{\partial}{\partial x} \left( \rho_{p,m} C_{p,m} T_w \right) = \frac{\partial}{\partial y} \left( \rho_{p,m} C_{p,m} T_w \right) \\
\frac{\partial}{\partial x} \left( \rho_{p,m} C_{p,m} T_w \right) &= \frac{\partial}{\partial y} \left( \rho_{p,m} C_{p,m} T_w \right)
\end{align*}
\]

where \(C_{p,m}\) is specific heat, \(\lambda\) is thermal conductivity, and \(T_w\) is temperature of water film.

Continuity equation of mixture film (vapor and air) is as following:

\[
\frac{\partial u_w}{\partial x} + \frac{\partial v_w}{\partial y} = 0
\]

Momentum equation of mixture film is:

\[
\rho_s \left( u_s \frac{\partial u_s}{\partial x} + v_s \frac{\partial u_s}{\partial y} \right) = -\frac{\partial p_s}{\partial x} + \eta_s \left( \frac{\partial u_s}{\partial x} + \frac{\partial u_s}{\partial x} \right) + \left( \rho_s \right) - \left( \rho_l \right) g
\]

where \(\rho_s\) is inlet density.

Energy equation of mixture film is given by:

\[
\frac{\partial}{\partial x} \left( \rho_s C_{p,m} T_s \right) = \frac{\partial}{\partial y} \left( \rho_s C_{p,m} T_s \right) = \frac{\partial}{\partial x} \left( \rho_{p,m} C_{p,m} T_s \right) = \frac{\partial}{\partial y} \left( \rho_{p,m} C_{p,m} T_s \right)
\]

Species diffusion equation is:

\[
\rho s \left( \frac{\partial w}{\partial x} + \frac{x}{\gamma} \frac{\partial w}{\partial y} \right) = \frac{\partial}{\partial y} \left( \rho_s D \frac{\partial w}{\partial y} \right)
\]

Turbulent dissipation rate \(\epsilon\) transport equation is described as:

\[
\rho u \frac{\partial \epsilon}{\partial x} + \rho \frac{\partial \epsilon}{\partial y} = \frac{\partial}{\partial x} \left( \eta_s \frac{\partial \epsilon}{\partial x} \right) + \frac{\partial}{\partial y} \left( \eta_s \frac{\partial \epsilon}{\partial y} \right) - C_\mu \frac{\epsilon^2}{k}
\]

Kinetic energy \(\kappa\) transport equation is written as:

\[
\rho u \frac{\partial \kappa}{\partial x} + \rho \frac{\partial \kappa}{\partial y} = \frac{\partial}{\partial x} \left( C_\mu \frac{\partial \kappa}{\partial x} \right) + \frac{\partial}{\partial y} \left( C_\mu \frac{\partial \kappa}{\partial y} \right) - \rho \epsilon
\]

where \(\eta_s\) is the turbulence coefficient of viscosity, \(\eta_s = \rho_s C_{p,m} \epsilon / k\), and \(C_{\mu}\) is the viscosity constant \(C_{\mu} = 1.42(I - (1/\gamma)(\eta_s/(\eta_s + \eta)))^{(1/\gamma)}\) \(\beta = 5\), \(\eta_s = 5.07 \times 10^{-6}\) \(\rho_s = 2.115 \times 10^{-3}\) \(\rho_l = 1.035\) \(\alpha = 0.0845\), \(\alpha = 0.3779\).
The principle of mixing derives material attribute equation is (Feddaoui, 2003):

\[ \rho = \alpha_r \rho_r + \alpha_w \rho_w + \alpha_v \rho_v, \quad \eta = \alpha_r \eta_r + \alpha_w \eta_w + \alpha_v \eta_v \]  

where \( \alpha \) is the volume fraction.

### 2.2 Boundary conditions

1. **Inlet boundary:** entrance is set to be velocity-inlet.

\[ U_{in, \text{air}} = \begin{cases} \frac{4 A_0}{t_0} (1 - (n + 1)) A_0 + u_0, & n_0 \leq t \leq (2n + 1) \frac{t_0}{2} \\ -\frac{4 A_0}{t_0} (4n - 1) A_0 + u_0, & (2n + 1) \frac{t_0}{2} \leq t \leq (n + 1) t_0 \end{cases} \]  

2. **Outlet boundary:** exit is set to pressure-outlet, and the pressure is atmospheric pressure.

3. **Wall boundary:** the wall is set to be no slip solid boundary, and the wall temperature is at the saturation temperature.

### 2.3 Parameter definition

Sherwood number is an infinite number reflecting the mass transfer phenomenon:

\[ Sh = \frac{h_m d}{K_z} \]  

where \( K_z \) is diffusion mass transfer coefficient of vapor in air, the equation is as follows:

\[ K_z = K_0 \left( \frac{T_{in, \text{air}}}{T_0} \right)^{1.5} \frac{p_0}{p} \]  

where \( K_0 \) is the characteristic coefficient of vapor in the air, \( K_0 = 2.55 \times 10^{-5} \text{ m}^2 \cdot \text{s}^{-1} \), \( T_0 = 298 \text{ K} \).

\( h_m \) is mass transfer coefficient of vapor in air:

\[ h_m = \frac{m_1}{\rho (1 - c_1)} \]  

where \( m_1 \) is the mass transfer flux, \( \text{kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \); \( c_1 \) is the relative humidity of the outlet.

The average Sherwood number:

\[ Sh_{\text{av}} = \frac{\int Sh d \tau}{\tau} \]  

The Womersley number is a dimensionless number of frequencies:

\[ W_0 = d \sqrt{\frac{2 \pi f}{\eta}} \]  

where \( f \) is frequency of pulsating airflow, Hz; \( \eta \) is fluid dynamic viscosity, \( \text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1} \).

Relative pulsating amplitude of air:

\[ A = \frac{A_0}{u_0} \]  

The dimensionless time:

\[ \tau = \frac{t}{t_0} \]

### 3. SOLUTION METHOD

#### 3.1 Design of numerical simulation

Commercial software ANSYS FLUENT 15.0 is adopted to this numerical simulation. Since the flow is in the axisymmetric, the problem can be simplified to a two-dimensional problem. Two-dimensional half-sectional model rotates around the axis for a complete round channel by using axisymmetric swirl function.

In the simulation, the implicit VOF multi-phases model, energy equation and RNG k-\( \varepsilon \) turbulence model are activated, and standard wall functions are adopted. The phase change evaporation equation is used in the study, setting air as the first phase, water as the secondary phase, and vapor as the third phase. PISO (Pressure implicit with splitting of operators) scheme is used to pressure-velocity coupling solution, and second order upwind is adopted to momentum, energy and swirl velocity; least squares cell based is adopted to gradient, and the first order implicit is adopted to transient formulation. The phase transition relationship between vapor and water is implemented by user defined function (UDF). At the standard atmospheric pressure, a phase transition between vapor and water occurs at the temperature 373.15 K. The initial parameters for numerical computation can be seen in Table 1.

<table>
<thead>
<tr>
<th>Grid independency tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>The results of numerical solutions are affected by grid number used in the simulation. Mesh independence verification is necessary to avoid convergence problems caused by the inappropriate use of grids. To check the adequacy of the numerical scheme adopted in the present study and, the procedure has been tested at Fig. 2 by comparing ( Sh_{\text{av}} ). It was found that in No. 4 to 6 grid sizes the difference in ( Sh_{\text{av}} ) is always less than 0.19%.</td>
</tr>
</tbody>
</table>

![Fig. 2 mesh independence verification](image)

<table>
<thead>
<tr>
<th>Grid number</th>
<th>( Sh_{\text{av}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>0.685</td>
</tr>
<tr>
<td>1500</td>
<td>0.6851</td>
</tr>
<tr>
<td>2000</td>
<td>0.6852</td>
</tr>
<tr>
<td>2500</td>
<td>0.6853</td>
</tr>
<tr>
<td>3000</td>
<td>0.6854</td>
</tr>
</tbody>
</table>

![Fig. 3 time step independency test](image)

<table>
<thead>
<tr>
<th>Time step/case</th>
<th>( Sh_{\text{av}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.6855</td>
</tr>
<tr>
<td>2</td>
<td>0.6856</td>
</tr>
<tr>
<td>3</td>
<td>0.6857</td>
</tr>
<tr>
<td>4</td>
<td>0.6858</td>
</tr>
<tr>
<td>5</td>
<td>0.6859</td>
</tr>
</tbody>
</table>

### 3.2 Grid independency tests

The initial parameters for numerical solution

<table>
<thead>
<tr>
<th>boundary phase</th>
<th>density ( \rho ) (kg/m(^3))</th>
<th>viscosity ( \eta ) (Pa·s)</th>
<th>velocity ( u ) (m/s)</th>
<th>temperature ( T ) (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>inlet air</td>
<td>1.225</td>
<td>1.7894×10(^{-5})</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>water</td>
<td>998.2</td>
<td>0.001003</td>
<td>0.3</td>
<td>373.15</td>
</tr>
<tr>
<td>pressure outlet</td>
<td>water</td>
<td>998.2</td>
<td>0.001003</td>
<td>373.15</td>
</tr>
<tr>
<td>vapor</td>
<td>0.5542</td>
<td>1.34e×10(^{-5})</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1 Initial parameters for numerical solution
As shown in Fig. 3, in order to assess the time step, five time steps are calculated, which are 0.0005 s, 0.001 s, 0.005 s, 0.01 s and 0.05 s. When the time step is irrelevant, when the time step is 0.001 s, the difference between the Sh values of the time steps before and after the time step is less than 0.018%, so it is more appropriate to use this time step for calculation.

4. RESULTS AND DISCUSSION

4.1 Different effects from uniform and pulsating airflow

Fig. 4 shows the mass flow rate as a function of evaporation time for both uniform ($u_{in, airflow}=3$ m/s) and pulsating airflow ($u_{airflow}=3$ m/s, $A_0=1$ m/s, $h_0=0.4$ s) conditions. As time goes by, the trend of Sh for uniform airflow tends to be smooth, and Sh of pulsating airflow shows periodic changes over time; the period of Sh is consistent with the period of airflow velocity.

For uniform flow, the evaporation of liquid film on the vertical inner surface of the circular tube is affected by the airflow. In the early stage of evaporation, the vapor mass flow rate increases. Over time, a stable vapor concentration boundary layer is formed on the surface of liquid film, causing the stability of mass transfer. For pulsating airflow, the vapor concentration boundary layer at the liquid film boundary is periodically destroyed, the vapor is carried away by the pulsating airflow, and the velocity of new vapor formation on the liquid film surface is accelerated, so the mass transfer changes with the cycle.

![Fig. 4 Sh vs. τ](image)

**Fig. 4 Sh vs. τ**

4.2 Effect of relative amplitude on relative evaporation

Fig. 5 shows the change of Sh under different relative amplitude A when $u_{airflow}=7$ m/s and $W_o=9.3$. It can be seen from Fig. 5 that as the relative amplitude A increases, Sh increases first and then decreases. When the relative amplitude $A=1/7$, the Sh reaches the maximum value, and the mass transfer effect of the pulsating airflow is relatively uniform. The airflow mass transfer effect is increased by 0.2%. This is because, with the increase of the relative amplitude, the change range of the airflow velocity becomes larger, and the disturbance to the boundary layer of the liquid film surface increases, thereby enhancing the mass transfer process.

![Fig. 5 Sh vs. A](image)

**Fig. 5 Sh vs. A**

4.3 Effect of pulsating airflow frequency on relative evaporation

Fraenkel and Nogueira et al (1998) and Hommema and Temple et al (2002) have shown that the heat transfer performance of pulsating airflow under dry conditions is better. Fig. 7 shows the change of Sh under different $W_o$ ($u_{airflow}=7$ m/s and $A=1/7$). It can be seen from the figure that when the $W_o$ is less than 10, as the $W_o$ increases, Sh increases, and its mass transfer effect is improved by 0.3% relative to the uniform airflow mass transfer effect. This is because the number of periodic changes of the pulsating airflow increases per unit time, and the number of times the vapor boundary layer on the liquid film surface is destroyed also increases. When the vapor boundary layer is destroyed, the vapor concentration gradient near the liquid film surface increases. The vapor diffuses in the direction of the gas stream with less concentration, and the convective mass transfer ability is enhanced. When $W_o>10$, as $W_o$ increases, the Sh decreases. This is because after the pulsating frequency of the airflow increases,
the pulsating airflow period decreases, which makes the pulsating airflow’s ability to perturb the liquid film boundary layer close, and the mass transfer effect becomes poor.

- The increase in pulsating amplitude promoted evaporation within a certain range. Compared with uniform velocity airflow, the relative evaporation increased by 0.3 % due to the effect of pulsating. The increase in pulsating amplitude promoted evaporation. Compared with uniform velocity airflow, the relative evaporation increased by 0.2 % by the effect of frequency. This was because pulsating airflow disturbed the boundary layer, and then took vapor away, which promoted to reproduce vapor.

- Compared with uniform velocity airflow, pulsating airflow can enhance the convective mass transfer effect of vertical flat falling film evaporation.

**ACKNOWLEDGEMENTS**

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**NOMENCLATURE**

- \( A \) pulsating relative amplitude
- \( A_0 \) inlet airflow pulsating amplitude (m/s)
- \( C_p \) viscosity constant
- \( C_p \) specific heat (kJ/(kg·K))
- \( D \) diameter of physical model (m)
- \( g \) gravitational acceleration (N/kg)
- \( H \) height of physical model (m)
- \( k \) kinetic energy
- \( k_1 \) thermal conductivit (W/(m·K))
- \( k_0 \) characteristic coefficient of vapor in the air
- \( r \) evaporation-condensation coefficient
- \( R \) radius of physical model (m)
- \( Sh \) Sherwood number
- \( Sh_{pj} \) average Sherwood number
- \( t_0 \) evaporation time (s)
- \( T \) system temperature (K)
- \( T_{\text{cons}} \) normal temperature (K)
- \( T_{\text{in,air}} \) inlet airflow temperature (K)
- \( T_{\text{in,water}} \) liquid film temperature (K)
- \( T_s \) saturation temperature (K)
- \( u_x, v \) velocity components in \( x, r \) coordinate directions, respectively (m/s)
- \( u_0 \) mean velocity of pulsating airflow (m/s)
- \( Wo \) Womersley number

**Greek Symbols**

- \( \delta \) liquid film thickness (m)
- \( \varepsilon \) turbulent dissipation rate
- \( \rho \) density (kg/m³)
- \( \alpha \) volume fraction
- \( \eta \) dynamic coefficient of viscosity (N·s/m²)
- \( \eta_t \) turbulence coefficient of viscosity
- \( \tau \) dimensionless time

**Subscripts**

- \( a \) air
- \( g \) mixture (air + vapor)
- \( v \) vapor
- \( w \) water

**REFERENCES**


