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Numerical investigations on the effect of swirling plume on natural draft dry cooling towers

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Abstract

Plume with swirling motions has been proven to be capable of enhancing the length of fire whirls. To investigate if the effect exists in natural draft dry cooling towers (NDDCTs), two methods to generate rotating motions inside cooling towers, including rotating the tower wall and adding tangential source term, have been simulated by FLUENT. The result shows that, in both cases, the air mass flow rate through the tower is enhanced as the swirl intensity increases at first and then decreases when the swirl number exceeds a critical value where vortex breakdown appears. It also illustrates that the swirl intensity generated by rotating the tower wall is relatively low due to the low viscosity of the air. On the other hand, adding source term shows to be able to generate swirl with higher intensity, and the results show that the tangential velocity profile utilized in the source term does not affect the performance significantly, but the tangential momentum is much more crucial instead. In addition, the vorticity-velocity interactions in swirling flows are utilized to explain the mechanism of the enhancement. Although swirl caused by artificial methods shows positive effects on the air mass flow rate enhancement, other verification schemes should also be investigated to confirm the effect in the later work.

Introduction

Swirling flow technology is one of the ways to produce high rates of entrainment of the ambient fluid and fast mixing, and it has been used in combustion equipment, heat exchangers and dust collectors and has shown certain improvements. It was also proposed to be applied in cooling towers in several patents in the last century. Different kinds of cooling towers wherein swirling flow is established were invented [1-3], yet most of the towers were natural draft wet cooling towers (NDWCTs). In NDWCTs, the main purpose of introducing swirl is to enhance the mixing between water and air, and thus improve the effectiveness of wet cooling towers. During this century, the swirling flows were once adopted to resist crosswind for NDWCTs [4, 5]. The simulation results indicated that the swirl increases the homogeneity if the flow field in the tower under the crosswind conditions. Additionally, the swirling motion of the flow inside the tower reduces the crosswind throttling effect in the outlet cross section for that it is able to disturb the vortices on the front side of the tower. Recently, Lu et al. [6] conceptually utilized several air jet inside a NDDCT to generate swirling plume inside the tower. The numerical results showed that the jet-induced swirl with specific jet nozzle configurations could increase the overall air flow rate more than 52% and the heat dump rate of the tower more than 38% under 35°C ambient temperature.

The lengthening high of fire whirls might provide some references for the enhancement of the air mass flow rate inside NDDCTs. After the first experiment on fire whirls in 1967 [7], related numerical and experimental research has been conducted. Focusing on the relationship between the flame height and swirling motion of fire whirls, the increase of flame height is resulted from the significant suppression of turbulent mixing between oxygen and fuel, and this suppression is caused by radial force balance and stable stratification of the radial centrifugal force field [8]. By applying the compensating regime of swirling flows, Klimenko and Williams [9] explained flame lengths of strong fire whirls are lengthening by the theory that the change in axial and radial velocities caused by compensating regime stimulates higher values of the mixture fraction at the axis. Base on the constant density assumption, the relationship between the normalized flame height and the modified Peclect number was found to be linear. In addition, similar theoretical conclusions have been made by Yu et al. [10] by taking the variable density effect into consideration.

Regardless of combustion reactions in fire whirls, the compensating mechanism was also adopted in hurricanes and other tornadic flows [11, 12], in which the flow circumstances are more similar with those in swirling plume enhanced NDDCTs except the boundary layer (the tower wall and heat exchanger). It should be mentioned that, in swirling flows, vortex breakdown appears once the swirl intensity reaches a critical degree, and it has been defined as an abrupt and sudden flow structure evolution accompanied by a free stagnation point on the axis followed by a reverse flow, which would be a negative effect on the heat rejection rate NDDCTs. Thus, from the aspect of engineering, it is important to avoid the occurrence of the phenomenon. This work numerically investigates how swirling motions influence the air flow through a short NDDCT for small solar thermal power plants. Two methods generating rotating motions inside the tower, including rotating the tower wall and adding tangential source terms, are adopted.

CFD Simulation Descriptions

A 20 meters height NDDCT in cylindrical shape is selected as the analytical objective in order to simplify the calculation and connect with the lab-scale NDDCT.

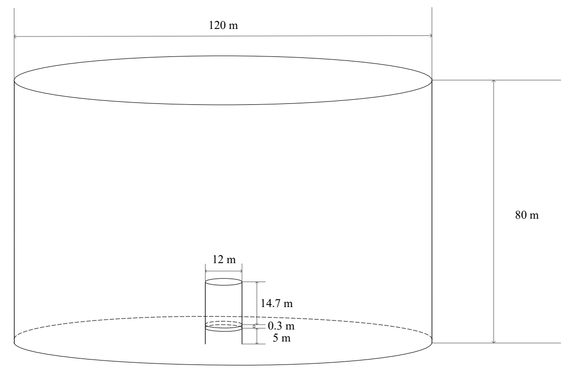


Figure 1. The size of the NDDCT and domain in the simulations.

The amount of mesh cells discretised from the whole domain is 1761638 in the cases. All the cases with different swirling flows at a certain ambient condition are based on the same mesh structure to be fairly compared. The air flow and heat transfer in NDDCTs are described and governed by a set of conservation equations. The discretization scheme is the second order of upwind scheme and the segregate algorithm is selected to be pressure-based SIMPLE. The realizable k-ε turbulence model will be adopted at this scenario due to the fact that, compared with other turbulence models, the solution converges more rapidly to low residuals. The heat transfer coefficient h, and the pressure loss Δp of the heat exchanger (u is the velocity) are based on the previous experimental data [13], but the resistance is assumed to be lower to avoid cold inflow phenomenon on windless condition, which is not the concern in this paper.

$$h = 190.95 + 549.22u - 150.07u^2 \quad (1)$$

$$\Delta p = 2.84u + 3.1u^2 \quad (2)$$

The ambient temperature and the heat exchanger temperature are set to be 30 °C and 55 °C, respectively. All the parameters are based on the numerical data from the tower top. As the heat exchanger temperature is set to be constant, the heat rejection rate should be chosen to represent the performance of the NDDCT. In this paper, however, the dimensionless area-weighted mean axial velocity (u_z/u_{z0}, where z represents the axial component; 0 represents the case without swirl) through the tower is selected to reflect the cooling tower performance since the axial velocity is also proportional to the heat rejection rate and it is more intuitive in the vorticity-velocity interactions.

Results and Discussions

Rotating the Tower Wall

The first attempt to generate swirling motions inside the tower is made by rotating the tower wall through the wall boundary conditions in the CFD software ANSYS FLUENT. The diagram is shown below.

Figure 2. Schematic diagram of swirling flows caused by rotating the tower wall.

As a result, the maximum tangential velocity will be near the wall, and it will decrease fast along the radial due to the low viscosity of air. The swirl number shown below is selected to represent the swirl intensity in this work (r is the radius; R is the maximum radius; θ represents the tangential component; A is the area).

$$S = \frac{\int r u_\theta \vec{u} \cdot d\vec{A}}{R \int u_z \vec{u} \cdot d\vec{A}} \quad (3)$$

By applying this equation, the relationship between the swirl number and the dimensionless axial velocity is first analysed (Figure 3). It is demonstrated that the enhancement of the axial velocity increases as the swirl number increases from 0 to 2.8, and decreases when the swirl number exceeds 2.8. This decrement is apparently caused by the occurrence of vortex breakdown (Figure 4).

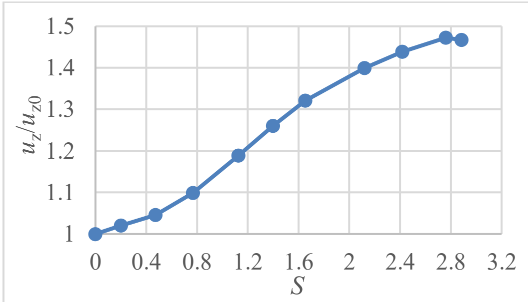


Figure 3. The axial velocity enhancement ratio versus the swirl number.

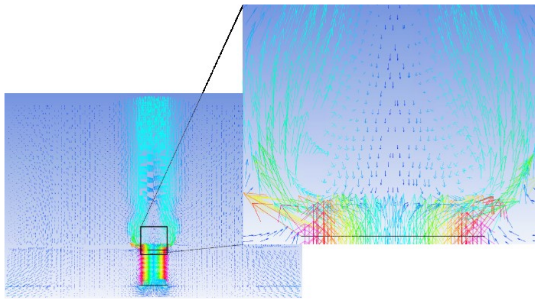


Figure 4. Vortex breakdown on the top of the tower.

The axial velocity profiles under different swirl intensities are investigated (Figure 5). It is found that the axial velocity profile is dominated by buoyancy when the swirl number is less than 1.0, which means the maximum axial velocity occurs at the centre. After the swirl number exceeds 1.0, the maximum value begins to occur close towards the wall. Once the swirl number is over 2.0, the axial velocity profile is dominated by the swirling motion and the maximum axial velocity occurs very close to the wall. The axial velocity profiles change is affected by the radial pressure gradient caused by the centrifugal effect of the tangential motions. Finally, when the swirl number is over 2.8, vortex breakdown appears at the top of the tower and negative axial velocity can be observed some distance from the wall. That the negative value occurs at this position should be caused by the tangential vortex which is a result of the occurrence of vortex breakdown.

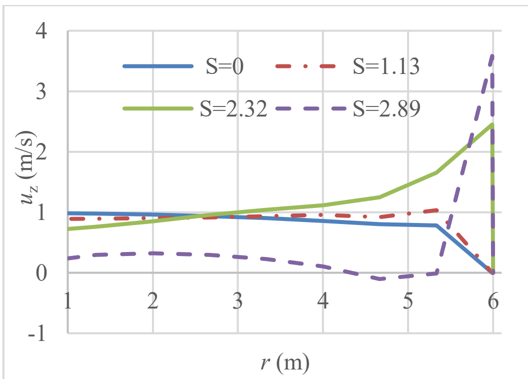


Figure 5. The radial distribution of the axial velocity

Adding Tangential Source Terms

In order to investigate if the tangential velocity profiles will influence the performance, adding source terms with different tangential velocity profiles inside the tower is simulated. Three different radial distributions of tangential velocity, namely first order, second order and third order, are investigated. At first, different maximum tangential velocities of each profile are carried out, and a same maximum tangential velocity is set for each velocity profile ($u_\theta = \frac{u_{\theta,max}}{R} r$; $u_\theta = \frac{u_{\theta,max}}{6R} r^2$; $u_\theta = \frac{u_{\theta,max}}{36R} r^3$) in different cases (Figure 6).

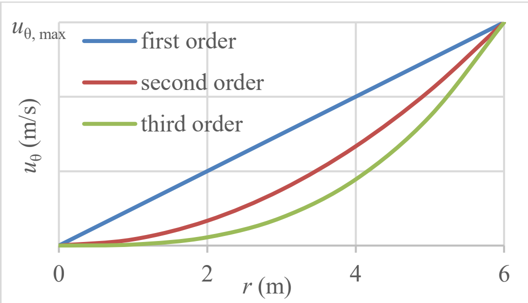


Figure 6. Tangential velocity profiles of source terms

In these preliminary cases, the swirl decay along the tower wall is not our concern, and to ensure the swirl intensity will reach its largest value on the tower top, all those tangential velocity profiles are achieved by adding source terms of the whole tower body on the top of the heat exchangers. The momentum source term can be added through the external body force term $\vec{F}$, in Navier-Stokes equation as follow.

$$\rho \frac{\partial \vec{u}}{\partial t} + (\rho \vec{u} \cdot \nabla)\vec{u} = -\nabla \mathrm{p} + (\nabla \cdot \bar{\bar{\tau}}) + \vec{F} \qquad (4)$$

To quantitatively compare how the swirling flows with different tangential velocity profiles influence the axial velocity, different maximum tangential velocities, including 1, 2, 3…, of each tangential velocity profiles are analysed. The result is shown below (Figure 7). The axial velocity of the air increases as the maximum tangential velocity increases, which means the air mass flow rate through the tower increases as the swirl intensity increases. This result agrees with the previous cases by rotating the tower wall. It also can be found that, among the three tangential velocity profiles, the swirl with the first order tangential velocity profile increases the axial velocity at the most, and then the swirl with the second order tangential velocity profile, and the swirl with the third order tangential velocity profile increases the axial velocity at the least. However, the angular momentum of these profiles is different from each other. Based on the same maximum tangential velocity, the case with the first order certainly owns the largest angular momentum, and then the case with second order, and the case with third order owns the least.

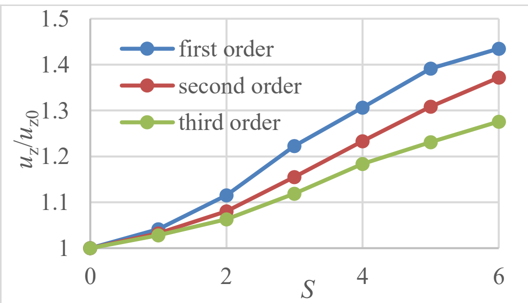


Figure 7. The dimensionless ratio of the axial velocities versus maximum tangential velocities of the three profiles

Thus, it is also necessary to compare them based on the same angular momentum which is contained in the swirl number definition. The relationship between the swirl number and the axial velocity increase is then investigated (Figure 8). Different from the cases with the same maximum tangential velocity, the changes show an overlap trend in the cases with the same swirl intensity, which means the tangential momentum instead of the tangential velocity profile is the most important variable. It is more evident, in comparison with the rotating tower wall cases, that the enhancement of the axial velocity increases slowly as the swirl number increases from 0 to 0.6, and then increases more rapidly as the swirl number rises from 0.6 to 2.0. After that, the enhancement of the mass flow rate begins to increase slowly again when the swirl number increases from 2.0 to 2.8, and finally it decreases when the swirl number exceeds 2.8. It should be concluded from this figure that the axial velocity increases, regardless of the tangential velocity profiles, as the angular momentum increases. Additionally, vortex breakdown occurs when the swirl number exceeds about 2.8 as well, and consequently the increment of axial velocity also decreases.

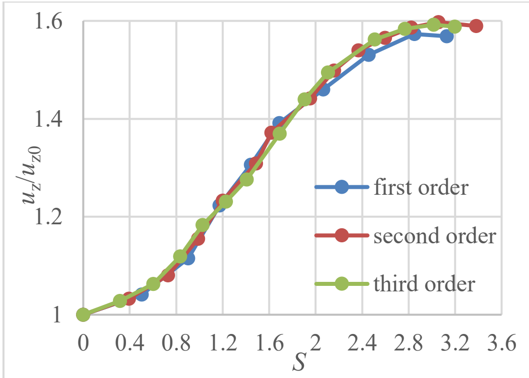


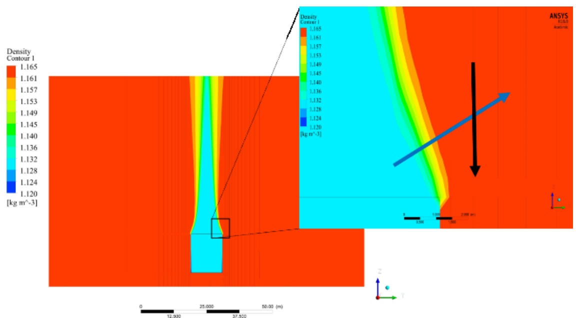
Figure 8. The dimensionless ratio of the axial velocities versus swirl numbers of the three profiles

Theoretical Analysis

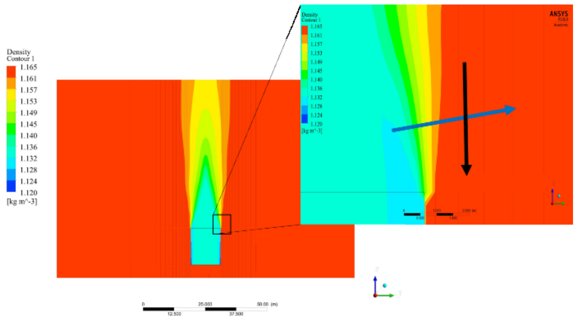
According the interaction between the axial velocity and the tangential vorticity, the axial velocity will increase with the increment of the tangential vorticity. Thus, the vorticity magnitude of swirling flows is investigated. Since the air through the tower can be regarded as incompressible flow, and steady state is the concern in the preliminary analysis, the vorticity equation can be written as (ω represents the vorticity):

$$(\vec{u} \cdot \nabla)\vec{\omega} = (\vec{\omega} \cdot \nabla)\vec{u} + \frac{1}{\rho^2} \nabla\rho \times \nabla \mathrm{p} + \nabla \times \left(\frac{\nabla \cdot \bar{\bar{\tau}}}{\rho} \right) \qquad (6)$$

Figure 9 shows the density contour on the top of the tower, and the black arrow represents the pressure gradient due to the gravity, while the blue arrow represents the density gradient. If the density gradient is perpendicular to the pressure gradient, the baroclinic torque (the second term on the right hand side of the equation) with swirl is larger than that without swirl. This is because the density gradient is resulted by the combination of the buoyancy and the centrifugal effect. This phenomenon explains that, in addition to the vortex stretching term and the viscosity torque term, at least the vorticity caused by baroclincity increases as the swirl intensity increases.



(a)



(b)

Figure 9. Density contours outside the tower in the cases without (a) and with (b) swirling flows

In addition, the relationship between the dimensionless tangential vorticity, and the swirl number is investigated. Numerical data of the third order tangential velocity profile source term are taken as an example to compare the changing trends. Obviously, the tangential vorticity rises as swirl intensity increases, and the trend is quite similar with the relationship between the rise of axial velocity and swirl number. However, the increment of tangential vorticity before swirl number exceeds 0.8 shows quite slow due to the mechanism that the small magnitude of the axial vorticity is insufficient to generate any significant level of the tangential vorticity[11]. The general increasing trend before swirl number exceeds 2.8 can be explained by the baroclinic torque and compensating regime, while the decreasing trend is caused by vortex breakdown as well. Once vortex breakdown occurs, downward flows near the axis on the top of the tower will counter the upward flow by buoyancy from the tower, as shown in figure 4. As a result, axisymmetric reverse tangential vortices will be generated against the axisymmetric tangential vortices caused by baroclinic torque, and consequently reduce the total amount of the tangential vorticity. This certain changing trend also demonstrates that the velocity-vorticity interaction could be the reason that swirling motions are capable of enhancing the air mass flow rate through NDDCTs.

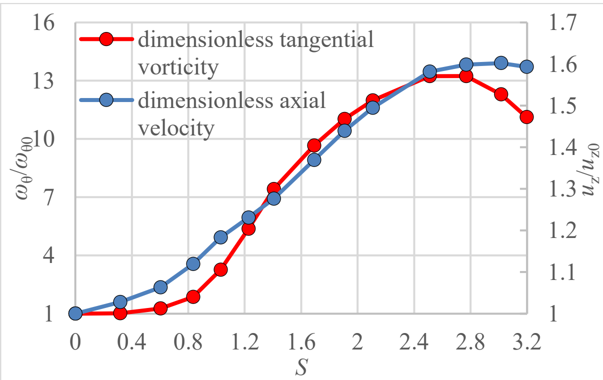


Figure 10. The comparison between the dimensionless tangential vorticity and axial velocity as swirl number rises

Conclusions

Preliminary CFD simulations of a 20 m height NDDCT shaped in cylinder have been investigated through rotating the tower wall and adding source terms inside the tower, respectively, to generate tangential velocity component on the buoyant plume. The results show that the increment of the axial velocity through the tower increases as the swirl number increases, but decreases when the swirl number exceeds the critical point due to the occurrence of vortex breakdown. In addition, the influence of swirling plume on the performance of the tower is barely affected by tangential velocity profiles, but mostly by the angular momentum. From the preliminary theoretical analysis, the interaction between the tangential vorticity and axial velocity could be the major factor that causes the increment of the air mass flow rate through the tower with the increment of the swirl intensity.

Acknowledgments

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