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Numerical Modelling on Solar Enhanced Natural Draft Dry Cooling Tower

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Abstract

Solar Enhanced Natural Draft Dry Cooling Tower is a new concept of hybrid cooling, in which solar heat collection is added to traditional natural draft dry cooling tower. Adding a solar-heated space to further heat the air after it leaves the heat exchangers increases the temperature difference between the inside and outside of tower, which leads to an increased air flow rate through the heat exchangers therefore better cooling performance. A one-dimensional model has been developed to predict its cooling performance by using MATLAB. The purpose of the present paper is to report on results of a detailed numerical analysis and to validate performance predictions from that one-dimensional model. A three-dimensional numerical model of a Solar Enhanced Natural Draft Dry Cooling Tower was created using the CFD software FLUENT. Reasonably good agreement is found between these two models.

Introduction

Compared to fossil-fired power generators, EGS power plants require much larger heat rejection systems due to their relatively low efficiencies. A typical coal-fired power plant would demand rejecting about 2 MW of heat for every MW of electricity it generates. A geothermal binary plant at half the efficiency of a coal-fired power plant would require rejecting about 5 MW of heat for each MW of electricity it generates [7].

Most geothermal power generation sites are located in arid areas where water is scarce and air cooling is the only option. Such site features feature high ambient air temperature at middle day hot hours. Hence, it would lead to high parasitic losses when using fan-driven cooling. Natural draft dry cooling therefore would offer a cost-effective alternative for such plants. However, natural draft dry cooling tower, as a dry cooling system, still suffers lower cooling efficiency at hot hours.

To manage to enhance cooling efficiency of dry cooling system at high ambient temperature, a novel dry cooling concept, namely solar enhanced natural draft dry cooling tower (SENDDCT) has been introduced [7], shown in figure 1.

A solar enhanced natural draft dry cooling tower consists of three major components namely heat exchangers, solar collector (sunroof and ground) and tower. The sunroof is a transparent circular roof which is placed around tower at certain height above the ground. Heat exchangers are placed vertically along the perimeter of solar collector. The tower is sited at the centre of sunroof. After flowing across heat exchangers, heated air is further heated up while flowing through the space under sunroof. The increased temperature differential between the air inside and outside the tower increases the buoyancy force, which leads to faster air flow across heat exchanger. Hence, higher cooling efficiency can be achieved.

In previous paper, a one-dimensional model had been developed through Matlab code to predict the cooling performance of SENDDCTs [7]. Computational fluid dynamic (CFD) analysis is conducted in this paper to verify the accuracy of the one-dimensional model. CFD software ANSYS FLUENT has proven to be an accurate and reliable tool to conduct fluid dynamic studies. Hence, a three-dimensional model including solar collector, heat exchangers and tower is built using ANSYS FLUENT.

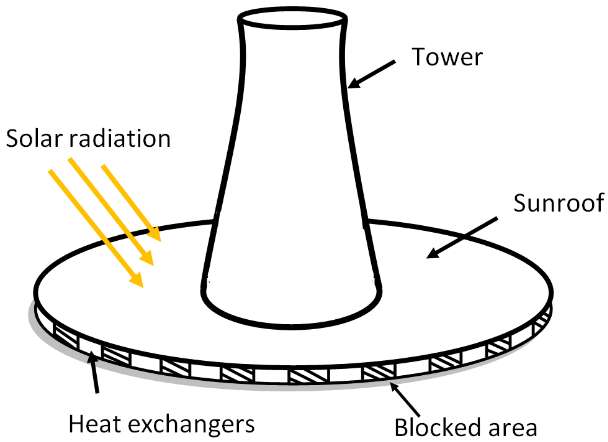

Figure 1. Schematic of solar enhanced natural draft dry cooling tower

Heat transfer and pressure drop analysis to heat exchanger

Heat exchanger plays a decisive role in any air cooling towers. Hence, hydraulic and heat transfer parameters of selected heat exchanger should be predetermined. A traditional three rows finned tube bundle is selected and used in the studies. Its dimensions are listed in table 1.

Description	symbols	Values
Row number	[-]	3 rows
height of heat exchanger (m)	H_{heatex}	15
number of tube per row	n_r	36
Transversal pitch (mm)	p_t	69.9
fin pitch (mm)	p_f	2.32
fin thickness (mm)	t_f	0.255
fin root diameter (mm)	d_r	39.88
fin diameter (mm)	d_f	69.84

Table 1. Dimensions of 3-rows finned tube bundle

In FLUENT, radiator boundary condition can be used to represent heat exchanger. It is considered to be infinitely thin wall and the heat transfer and pressure drop through it can be formulated as below

$$q = A_{fr} h (T_{wi} - T_{ao}) \quad (1)$$

$$\Delta P = k \frac{1}{2} \rho_{ai} V_a^2 \quad (2)$$

Where, A_{fr}, ρ_{ai}, T_{ao} are heat transfer area, density of inlet air and air outlet temperature, respectively. Both heat transfer coefficient h and pressure drop coefficient k are functions of air velocity normal to radiator. These two coefficients can be derived by software ASPEN. In this study, the inputs to ASPEN are air velocity V_a, ambient air temperature, T_{ai} (30°C), water inlet temperature T_{wi} (60°C), dimensions of three-row finned tube bundle and water mass flow rate, M_w (2375 kg/s). By processing the data and conducting curve fitting, the relations between heat transfer coefficient and air velocity as well as the pressure drop coefficient and air velocity are formulated in the form of polynomial, as follows:

$$h = 2038 - 3380V_a + 3433V_a^2 - 1608V_a^3 + 282.4V_a^4 \quad (3)$$

$$k = 74.19 - 100.9V_a + 91.44V_a^2 - 38.97V_a^3 + 6.218V_a^4 \quad (4)$$

These equations above are used in both 1-D and 3-D model to evaluate the cooling performance of heat exchangers.

CFD modelling and validation for one-dimensional model

Mesh, boundary conditions and materials

Patohr did two-dimensional numerical analysis on solar chimney power plant using FLUENT in 2004. In his study, the solar radiation was defined as heat flux stored in a thin layer at the ground surface [2]. Xu conducted two-dimensional numerical research on solar chimney power plant based on the model developed by Pasthor and Gurlebeck [6]. The simulation results had been compared with the experimental results collected from a prototype solar chimney power plant in Spain. The comparison indicated that using a thin layer (with heat flux stored) to represent the solar irradiance is simple and the result is accurate. In 2010, Ming used this boundary setting to develop a three-dimensional model for a 10 MW solar chimney power plant [1].

Therefore, the same setting is used in this three-dimensional numerical analysis on SENDDCT. Since simulating entire solar enhanced natural draft dry cooling tower is time-consuming, only 30-degrees sector of the entire cooling system is modelled as shown in figure 2. The 3-D model includes three zones: solid ground, the air inside of SENDDCT, and the air outside of SENDDCT. The total heat transfer and air mass flow rate in whole SENDDCT are 12 times the values computed in this sector. Both unstructured tetrahedral and hexahedral mesh are used. Grid-independence is tested by varying the number of gird from 4,000 to 700,000 until consistent results are reached (less than 0.5% error).

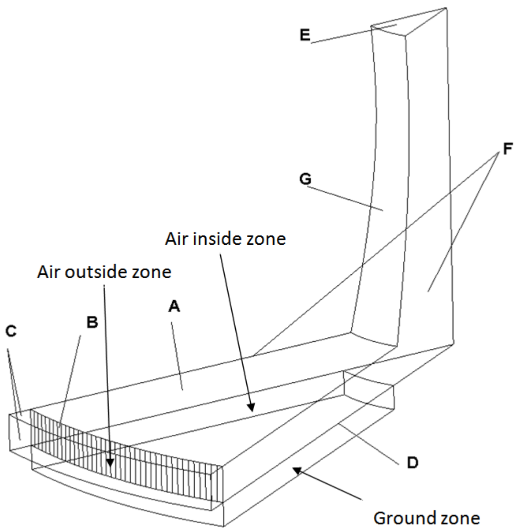

Figure 2. 3-D model of SENDDCT

Proper boundary conditions must be applied to achieve accurate results. As shown in figure 2, symmetry boundary conditions are applied at both sides of the sector. Pressure inlet boundary conditions are specified at inlet faces of air outside zone. Radiators to represent the heat exchangers are applied at the inlet face of air inside zone. The heat transfer coefficient and pressure drop coefficient are specified according to equation (3-4). Zero static pressure is applied at the tower exit. Sunroof is represented by a wall, which is capable of conducting radiation and convective heat transfer. Solar radiation is regarded as heat flux in a thin layer on the ground surface. This heat source conducts heat transfer with the air inside and the ground. The rest of the boundaries are described as adiabatic and slip-free walls. Detailed boundary settings are listed in table 2.

Face	position	Type	value
Sunroof	A	Wall	T_a=303.15 K, Convective heat transfer coefficient:h_s=14 W/m^2.K
Heat exchangers	B	Radiator	T_{wi}=333.15 K, equation (3-4)
Inlet faces of air outside zone	C	Pressure inlet	T_{ai}=303.15 K, Air inlet pressure: P_i=0 Pa
Conjunction wall between heat collection space and ground	D	Wall	Heat flux (W/m^3): $q_f = s\varepsilon_s \alpha_{ab} / L_s$ Solar radiation: s Transmittance of sunroof: ε_s=0.84 absorptivity of soil surface: α_{ab}=0.9 thickness of layer: L_s=0.0001m
Tower exit	E	Pressure outlet	Air outlet pressure: P_o=0 Pa
Both sides of sector	F	Symmetry	[-]
Tower shell	G	Wall	Adiabatic free-slip
The rest of faces of ground		Wall	T_g=300 K

Table 2. Boundary condition settings

The material of ground is selected as sandstone and air is regarded as ideal gas. The properties of the sandstone and air are listed in table 3.

	Sandstone	Idea gas
Thermal conductivity (W/mK)	1.83	0.0265638
Specific heat (j/kgK)	710	1008
Density (kg/m^3)	2160	[-]
Viscosity (kg/ms)	[-]	1.87e-5
Molecular weight (kg/kgmol)	[-]	28.966

Table 3. Properties of sandstone and ideal gas

Solver

The SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm is used in this numerical simulation with discretization for governing equations under second order accuracy. Al-Waked and Sangi employed standard k- ε turbulence model to model natural draft dry cooling tower and solar chimney power plants, respectively [3, 4, 5]. Standard k-ε model works well with their modellings. Hence, considering our computational resources and previous studies, we adopt standard k-ε model to demonstrate turbulence condition in SENDDCTs.

During running test cases in FLUENT, computations would not complete until residuals of all governing equations reach their minimum respectively.

Validation for one-dimensional model

To validate developed one-dimensional model, a test case is run in both one-dimensional model and three-dimensional model. In this test case, 485 3-rows finned tube bundles are fully covered the perimeter of solar collection space, which make sunroof diameter reach to 390 m. Some major operating and ambient parameters are as follows: H_c=140 m, T_{ai}=30^{o}C, T_{wi}=60^{o}C, D_{base}=101 m, D_{chi}=70 m, H_{heatex}=15m, M_w=2375 kg/ s, and s=1000W/m^2. H_c, D_{base}, D_{chi} and M_w refer to tower height, tower base diameter, tower exit diameter and water mass flow rate, respectively. The dimensions of involved heat exchangers are listed in table 1. The temperature field and vector field are shown in figure 3 and figure 4, respectively.

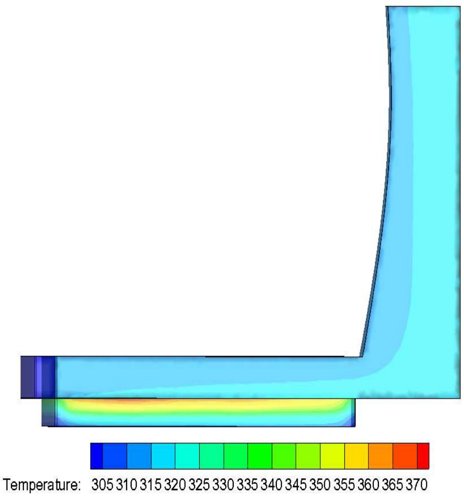

Figure 3. Temperature field of the solar enhanced natural draft dry cooling tower

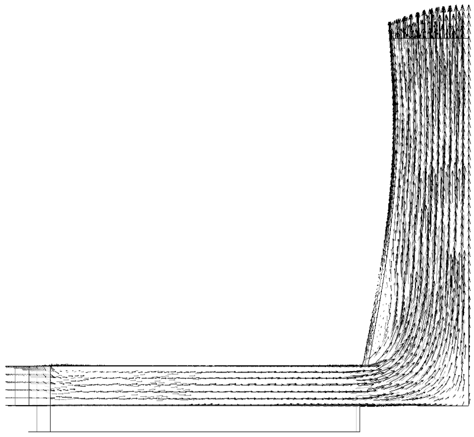

Figure 4. Vector field of the solar enhanced natural draft dry cooling tower

Figure 5-6 show temperature distribution and velocity distribution within both 3-D and 1-D models are quite consistent with each other. The total heat transfer rate calculated by one-dimensional model is 265871056 W whereas that is 260400000 W in FLUENT. This leads to 2% difference, which is acceptable. In one-dimensional model, pressure drop through heat exchanger and pressure drop due to flow acceleration are 23.3268 Pa and 5.6 Pa respectively. On the other hand, three-dimensional model gave slightly larger values in pressure drops due to slightly larger air velocity computed by FLUENT, as shown in figure 7. Because good agreements between FLUENT and 1-D model results on the same test case, a conclusion can be made that one-dimensional model by using MATLAB is reliable to predict the performance of any SENDDCT if the outside edge area of the solar collector is fully covered by the heat exchangers.

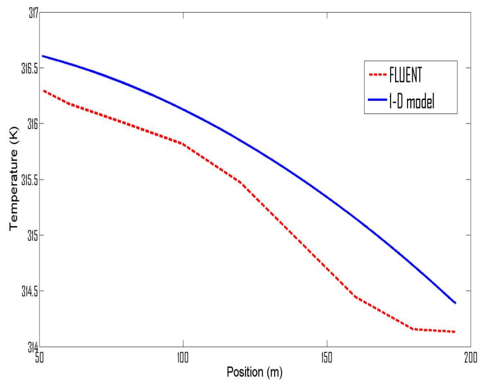

Figure 5. Temperature distributions obtained from FLUENT (3-D model) and the author-developed one-dimensional model [7]

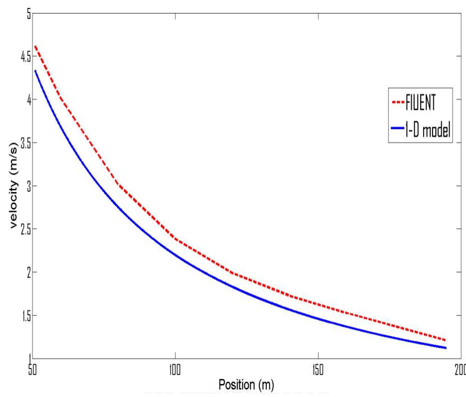

Figure 6. Velocity distributions obtained from FLUENT (3-D model) and the author-developed one-dimensional model

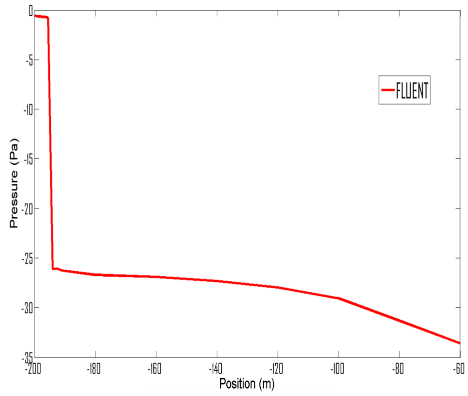

Figure 7. Pressure distributions obtained from FLUENT (3-D model)

Conclusions

Three-dimensional numerical simulation for Solar enhanced natural draft dry cooling tower, which consists of heat exchanger, solar collection space and tower, is carried out by using ANSYS FLUENT. A test case was run with both FLUENT and one-dimensional model introduced in previous paper. A satisfactory agreement is found between the results of three-dimensional model and one-dimensional model. It proved that the developed one-dimensional model is reliable to predict the performance of SENDDCT if outside edge area of solar collector is fully covered by the heat exchangers.

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