*International Journal of analytical and Numerical Methods in Mechanical Design*
*Vol 3., Issue 2, Summer & Autumn 2024, 21-27*

# Numerical modeling and analysis of smoke injection into the Heller cooling tower and its effect on the performance of Shahid Rajaei power plant with thermal and combined cycle in wind conditions

**Asadollah ghaffari aghababaei***
Department of Mechanical Engineering, Qazvin Branch, Islamic Azad University, Qazvin, Iran
Received 20 August 2024, Accepted 28 October 2024

**Abstract**

The performance of a Heller tower depends on known parameters and environmental conditions such as temperature, relative humidity, wind, etc., so that in addition to temperature and density, the flow rate of air sucked into the tower will affect its efficiency. In windy conditions, due to the disruption of the symmetry of the pressure distribution around the tower and also the creation of a capping phenomenon at the top of the tower, the inlet flow rate and the efficiency of the cooling tower are reduced, which leads to a decrease in the overall performance of the power plant. One of the methods that has been proposed to improve tower efficiency is to inject exhaust smoke from a boiler or smoke generator into the cooling tower. In the present study, the results of the numerical analysis, in the states without smoke injection and with smoke injection under the design conditions of the tower and wind, have been used for the thermodynamic, energy and exergy analysis of different power plant components. The results of the numerical simulation show an increase in the thermal power of the cooling tower by 16.7 MW, the efficiencies of the first and second laws of the power plant by 92% and 86% in the condition of wind blowing at a speed of 20 m/s under the influence of smoke injection, compared to the condition without smoke injection.

***Keywords***: Heller cooling tower; exhaust smoke injection; wind speed, natural convection; thermal and combined cycle, heat exchanger and thermal process.

## 1 - **Introduction**

The use of Heller dry cooling towers has grown significantly due to the scarcity of water resources. Their performance depends greatly on environmental conditions, So that in addition to the temperature and density of the inlet, the flow rate of the sucked air to the tower will also directly affect its efficiency. According to many researches, wind blowing due to disturbing the symmetry of pressure distribution around the tower and also due to the creation of a capping phenomenon on the top of the tower, causes a decrease in the flow rate of the incoming air to the tower as a result of its performance loss. One of the methods proposed to improve the performance of the tower in windy conditions is the injection of exhaust smoke from a steam boiler or smoke generator with a temperature of 140 degrees Celsius into the cooling tower, which, according to the researches, improves the performance conditions and increases the flow rate of the incoming air into the tower compared to the condition without smoke injection. It should be noted that the use of this method has disadvantages such as the increase in the output back pressure from the gas turbines, pressure and temperature drops due to the creation of the smoke injection channel, and the noise created by the smoke injection nozzle, as well as the construction costs, which should be analyzed and analyzed in addition to the improvement of the tower performance and power generation in the steam turbine, and the results should be analyzed based on the advantages and disadvantages. So far, there have been many studies on the performance of Heller dry cooling towers, all of them have investigated the destructive effects of adverse wind on their performance and have provided solutions to eliminate these effects. Aloked and Behina [1] performed a three-dimensional simulation of the flow in and around a dry natural suction tower. Ghaffari and Glenshan [2] and Jahangiri and Rahmani [3]; investigated the effects of wind and the use of windbreak walls on the dry cooling tower. Eldridge et al. [4] and Cooper et al. [5]; investigated the effect of placing a heat source inside the wet tower on the performance of naturally drawn cooling towers. Jahangiri and Glenshan [6-8] investigated the improvement of the thermal performance of a Heller tower in the vicinity of wind, with the help of injecting smoke from the combined cycle power plant into it. Madnia et al. [9]; experimentally investigated crosswinds on cooling towers and came to the conclusion that crosswinds affect the air flow inside the cooling tower and considered the windbreak wall to be an important factor to prevent cooling tower performance and power plant efficiency. As is known, the performance of the tower will affect the entire power plant cycle, and improving its performance will also lead to improved cycle efficiency.

Corresponding author Email address: ghaffari1351@yahoo.com

Therefore, in the first stage of this research, numerical modeling and investigation of the effect of wind on the performance of the Heller cooling tower in two states without smoke injection and with smoke injection, and then thermodynamic investigation and exergy analysis of various components of the combined cycle power plant, and finally, considering the advantages and disadvantages, its effect on the overall efficiency of the law of the first and second laws of thermodynamics of the power plant is expressed.

## 2- Problem statement:

In order to investigate the effect of wind on the performance of Shahid Rajaee combined cycle power plant, first all its components are modeled for operating conditions. Then, using the results of numerical solution, the performance and behavior of the tower under different wind conditions on the condenser, steam turbine, and finally on the entire combined cycle are simulated. Then, in order to improve the performance of the cooling tower by injecting exhaust smoke into the cooling tower, all components of the power plant will be modeled using computational fluid dynamics under different wind conditions, so that exergy analysis and the efficiencies of the first and second laws of thermodynamics will be calculated and analyzed based on the resulting data.

## 3- Modeling of Heller tower and governing equations:

The Heller cooling tower, as shown in Figure 1, acts like a chimney into which air flow is drawn by natural convection. The cooling tower under study is one of the cooling towers of the Shahid Rajaee Qazvin combined cycle power plant, and its geometric information was obtained based on the data as shown in Figure 1.

Fig 1. Schematic of the Heller cooling tower of Shahid Rajaee Power Plant with combined cycle

The heat transfer between the hot water entering the heat exchanger and the cooling air entering with natural suction is expressed by the following relationship:

$$\mathbf{(1)} \quad \boldsymbol{Q} = (T_{wm} - \boldsymbol{T_{ai}})$$

In the above relationship, $T_{wm}$ is the average water temperature of the radiators and $\boldsymbol{T_{ai}}$ is the inlet air temperature. The main flow equations include the continuity, momentum, and heat transfer equations, which satisfy the conservation of mass, momentum, and energy, respectively, and are written as follows:

$$\mathbf{(2)} \quad \boldsymbol{\nabla . V = 0}$$

$$\mathbf{(3)} \quad \boldsymbol{(V.\nabla)V = -\frac{1}{\rho}\nabla P + \nabla\left(\frac{\sigma}{\rho}\right) - \beta(T - T_a)g + S}$$

$$\mathbf{(4)} \quad \boldsymbol{\rho(V.\nabla)T = \nabla[(\Gamma + \Gamma_t)\nabla T] + Q}$$

Considering the use of the standard k-ε turbulent model, the turbulent kinetic energy k and the diffusion rate ε can be expressed as the following equations.

$$\mathbf{(5)} \quad \boldsymbol{(V.\nabla)k = \nabla\left[\left(\upsilon + {}^{\upsilon_t}/_{\sigma_k}\right)\nabla k\right] + P + G - \varepsilon}$$

$$\mathbf{(6)} \quad (\boldsymbol{V}.\boldsymbol{\nabla})\boldsymbol{\varepsilon} = \boldsymbol{\nabla}\left[\left(\boldsymbol{\upsilon} + {}^{\boldsymbol{\upsilon_t}}/_{\boldsymbol{\sigma_\varepsilon}}\right)\boldsymbol{\nabla\varepsilon}\right] + \boldsymbol{c_{1\varepsilon}}\frac{\boldsymbol{\varepsilon}}{\boldsymbol{k}}(\boldsymbol{P} + \boldsymbol{G}) - \boldsymbol{c_{2\varepsilon}}\frac{\boldsymbol{\varepsilon^2}}{\boldsymbol{k}}$$

In the above relationship, P is the kinetic energy produced by turbulence and G is the kinetic energy produced by buoyancy.

By applying the boundary conditions, the flow and heat variables are determined at the entrance of the physical boundaries of the domain, which can be seen in Figure 2 how to choose them.

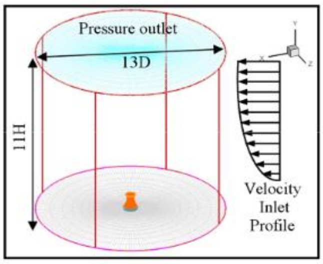


Fig 2. View of the solution domain and boundary conditions

The wall boundary condition is used for solid boundaries such as the ground, the tower shell, and the pipes that are inserted into the tower to inject hot smoke. Also, the boundary condition of the inlet velocity is used to define the velocity and scalar properties of the inlet flow to the boundary. Wind speed components in the flow direction are equal to wind speed and other components are equal to zero. The ambient air temperature is considered constant and equal to 288 K for all wind speeds and smoke injection modes. It is worth mentioning that in the boundary condition, the radiators used to model the heat exchangers of the tower are considered to be infinitely thin. and their pressure drop and heat transfer coefficient are considered proportional to the air flow according to the following relations.

$$\mathbf{(7)} \quad \boldsymbol{\Delta p = 2.1\dot{m}^{1.76} + 0.06\dot{m}^2}$$

$$\mathbf{(8)} \quad \boldsymbol{h = 1374\dot{m}^{0.515}}$$

## 4- Networking and solution scope:

In order to investigate the effect of wind blowing and smoke injection on the results of thermal flows and heat transfer on the cooling tower, after studying the network and checking the non-dependence of the solution on the network, organized networks have been used, as shown in Figure 3.

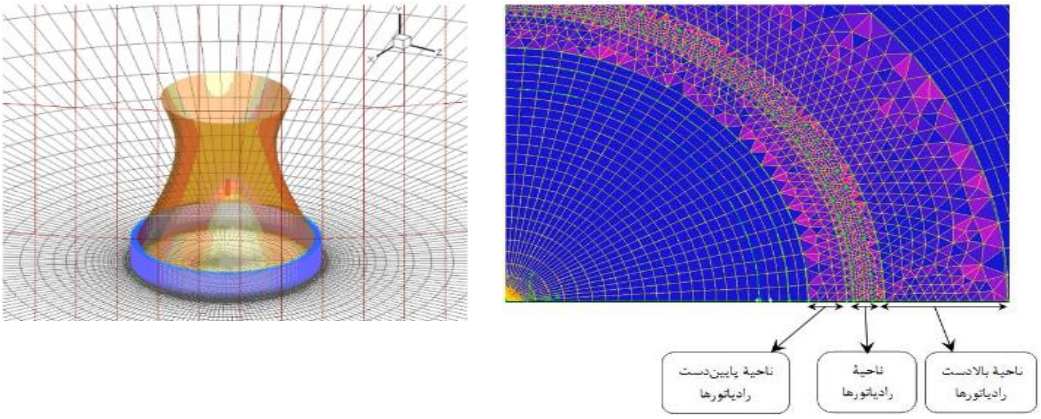


Fig 3. View of how the computational domain is networked

To ensure that the solutions are independent of the network, according to the research of Jahangiri and Golenshan [1], heat transfer from the tower for 4 different network types is compared in Table 1. And considering the maximum error of one percent, the number of network 2874760 has been chosen as the most suitable network.

Table 1
Heat rejected from the tower for different networks

| Mode | Number of networks | Heat transfer of exchangers |
|---|---|---|
| 1 | 2220220 | 213.5 |
| 2 | 2516929 | 213.68 |
| 3 | 2874760 | 213.81 |
| 4 | 3017660 | 213.86 |

**5- Reviewing the results of numerical solution:**

Table 2 shows the results obtained from the numerical solution in comparison with its nominal value in the manufacturer's catalog under design conditions and the actual values measured in one of the cooling towers of the Shahid Rajaee combined cycle power plant. As it can be seen, the results obtained from the numerical solution are in good agreement with the results reported by the manufacturing company in nominal conditions.

Table 2
Heat rejected in the exchangers of the Heller cooling tower of Shahid Rajaee Power Plant with combined cycle (without wind effect)

| State | Design conditions [7] | Numerical simulation | Measured values [7] |
|---|---|---|---|
| Dissipated heat | 214.3 | 213.81 | 202.8 |

**6- The computational fluid dynamics results of the Heller cooling tower in AnsysFluent software:**

The injection of exhaust smoke into the tower in windy conditions can lead to improvement of the cooling tower performance, as shown in Figure 4, which compares its positive effect in windy conditions without smoke injection. It should be noted that this injection was carried out using a nozzle with a diameter of 2m and an exit velocity of 91.21m/s. In the research of Jahangiri and Glenshan [7], the effect of the height of the smoke discharge and the diameter of the smoke discharge nozzle on the performance of the tower was investigated and the optimal mode of the nozzle with a diameter of 2m and a height of 35m was suggested. Therefore, in the present research, the results of the optimal smoke injection mode for winds of 0, 5, 10, 15, and 20 m/s have been used to examine the results of solving the flow and energy equations after ensuring convergence in the form of temperature distribution, pressure distribution, and air velocity vectors. According to the diagram in Figure 4, the thermal performance of the tower decreases due to the wind, which can be attributed to the reduction of the air flow into the tower due to the creation of secondary flows and the flow moving away from the normal suction mode, which can be seen in Figure 5.

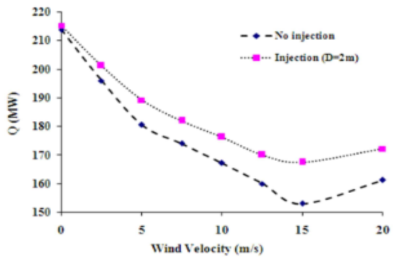


Fig 4. The use of smoke injection in the cooling rate of the Heller Tower in the conditions of wind blowing with different speeds

As can be expected, the injection of hot smoke leads to increased air suction into the tower, thereby increasing the amount of heat removed from the tower. Figures 5 and 6 (in the case without smoke injection and with smoke injection, respectively) show the velocity vectors in the condition of 10 m/s wind and in the vertical cross section.

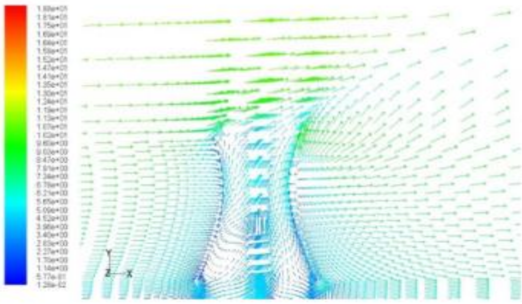

Fig 5. Velocity vectors in cross section z= ٠and wind blowing 10m/s (Without smoke injection)

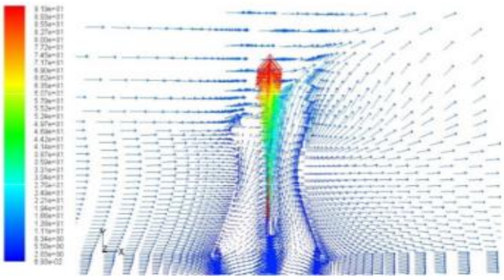

Fig 6. Velocity vectors at the section z= ٠and wind blowing 10m/s (with smoke injection)

As can be seen from Figure 5, the wind flow acts like a horizontal system on the outlet opening of the tower, and thus greatly reduces the natural suction of the tower While by injecting hot smoke, the effect of the capping phenomenon on the top of the tower is reduced and the flow of air passing through the tower increases. In the natural suction mode (without wind) due to the symmetry of the pressure distribution around the tower and the flow field inside the tower, the temperature distribution is also completely symmetrical and the amount of heat removed from all exchangers is the same. But in the case of wind, due to the asymmetry of pressure distribution around the tower, the flow inside the tower is out of symmetry and the amount of heat rejected from the exchangers around the tower will not be the same; so that the front exchangers (facing the wind) dissipate more heat than the side and rear exchangers due to the passage of more air into them And in total, the heat rejected from the tower is reduced compared to the state without wind, which means an increase in the temperature of the water exiting the tower and as a result, a decrease in the production power and efficiency of the steam cycle in the power plant.

## 7- Thermodynamic analysis of smoke injection into the Heller cooling tower in Shahid Rajaei power plant with a combined cycle

The mass, energy and exergy equations used for each of the components in a thermal system can be expressed as an exergy balance using the combination of the first and second thermodynamic laws:

$$\dot{E}_w = -\frac{d}{dt}(E + P_o V - T_o S) + \sum_{i=1}^{n} \dot{Q}_i \left(1 - \frac{T_o}{T_i}\right) + \sum \dot{m}_{in}(h_{in}^t - T_O s_{in}) - \sum \dot{m}_{out}(h_{out}^t - T_O s_{out}) - T_O \dot{S}_{gen} \quad (9)$$

Each of its terms are:

$-\frac{d}{dt}(E + P_o V - T_o S)$, It expresses the non-flow exergy stored in the control volume.

$\sum_{i=1}^{n} \dot{Q}_i \left(1 - \frac{T_o}{T_i}\right)$, It represents the exergy of the heat exchanged by the system, which takes place at temperature $T_i$.

$\sum \dot{m}_{in}(h_{in}^t - T_O s_{in})$, Expressing the exergy of the input current.

$\sum \dot{m}_{out}(h_{out}^t - T_o s_{out})$, Expressing the exergy of the output current

$-T_O \dot{S}_{gen}$, It represents the amount of irreversibility of the system that is created by the production of entropy in its processes.

For accurate exergy analysis and calculation of irreversibilities in the Shahid Rajaee Combined Cycle Power Plant, each of its components must be considered as a control volume And he wrote and solved the equations of energy conservation and exergy balance for it. It should be noted that for the combustion chamber of the gas turbine where the chemical process takes place, changes in chemical exergy are also observed.

## 8- Investigating numerical and thermodynamic results of Shahid Rajaei power plant with combined cycle

In order to investigate the effect of wind blowing on the performance of Shahid Rajaei power plant with combined cycle, first all its components, including gas turbine and steam turbine unit components, have been modeled for the operational conditions. The recycling boiler used is a double-pressure recycling boiler, the upper pressure of which is set at 104 bar and the lower pressure at 18.2 bar. The environmental conditions are considered as temperature and pressure of the power plant design, respectively, 15 degrees Celsius and 0.867 bar. As it is clear, the increase in pressure behind the gas turbine leads to a decrease in its production power which according to the length of piping from the end of the combined cycle to the Heller cooling towers And according to the modeling and thermodynamic calculations, it will have a negative effect directly on the gas turbine production power And according to the modeling and thermodynamic calculations that will directly affect the gas turbine's production power, there will be a pressure drop of about five kilowatts on the way. In the following, energy and exergy equations have been solved for all components in the combined cycle of Shahid Rajaei power plant And examples of these results are compared with real data And the results of that, including the production power of the gas turbine and the production power of the steam cycle, are given in Table 3.

Table 3
Actual values and thermodynamic modeling results of the combined cycle of Shahid Rajaei

| Kind of Power Plant | Gas turbine production power (MW) | Steam turbine production power (MW) |
|---|---|---|
| Actual values | 116.2 | 98.2 |
| Modeling results | 114.7 | 95.6 |

As can be seen, the modeling results are largely closer to the real values and their differences are minor. Therefore, it can be concluded that the modeling is done correctly and the obtained results are also valid for other states. After writing the equations for all cycle components and solving them, The exergy destruction values of various cycle components and the first and second law efficiencies are determined in two cases without smoke injection and with smoke injection for different wind speeds. Figures 8 to 10 show the exergy loss values in different components of the combined cycle. Injecting the exhaust smoke from the recovery boiler into the cooling tower increases the back pressure of the turbine and as a result reduces the production power and also reduces the efficiencies of the first and second laws of thermodynamics in the gas turbine cycle. But increasing the back pressure of the gas turbine increases the temperature of the exhaust smoke Although it has a negative effect on the gas turbine cycle, it increases the temperature of the high pressure superheater steam And as a result, the production power and efficiency of the steam cycle increases. Reduction of the production power of the gas turbine due to the injection of smoke into the cooling tower for low wind speeds has an adverse effect on the overall performance of the power plant. Because the decrease in the production power of the gas turbine is more than the increase in the power of the steam turbine. But as seen from figure 7 With the increase of wind speed to more than 3m/s, the positive effect of smoke injection on the steam cycle is overpowered by its negative effect on the gas turbine And overall it increases production capacity And with increasing wind speed, this positive effect increases And the difference in production power between the combined cycle power plant that uses the method of smoke injection into the cooling tower increases compared to the cases without smoke injection. Under windy conditions, the flow rate of air passing through the cooling tower decreases, which reduces the thermal power of the cooling tower. By reducing the amount of heat dissipated by the cooling tower, the total production power of the steam cycle is reduced In order to maintain the vacuum of the condenser and prevent its pressure from increasing, power reduction is done by reducing the mass flow rate of steam in the steam cycle. Therefore, the steam cycle production power and the exergy destruction rate of the components are also reduced And as a result, the efficiency of the first and second laws, which express the performance of the cycle, is reduced in windy conditions.

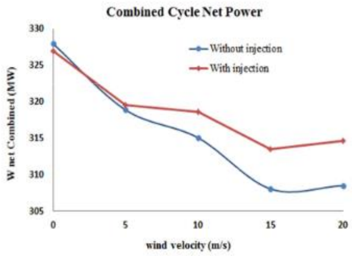


Fig 7. The net power generated in the entire combined cycle in the conditions With and without exhaust smoke injection into the Heller cooling tower

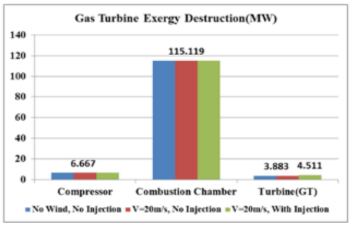


Fig 8. Exergy losses of main gas turbine components for three modes Without smoke injection and without wind blowing, without smoke injection and with wind blowing, with smoke injection and with wind blowing

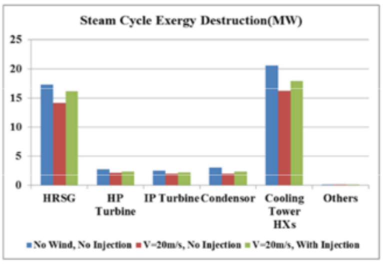


Fig 9. Exergy losses in the main components of the steam cycle for three modes Without smoke injection and without wind blowing, without smoke injection and with wind blowing, with smoke injection and with wind blowing

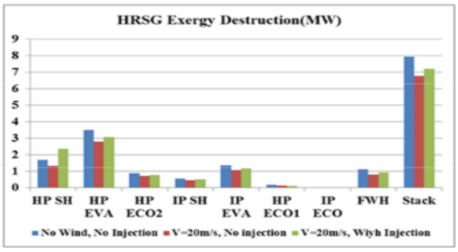


Figure 10- Exergy losses in the main components of the combined cycle for three modes Without smoke injection and without wind blowing, without smoke injection and with wind blowing, with smoke injection and with wind blowing

In the condition of wind blowing with the same speed under the condition where smoke is injected into the cooling tower, The flow rate of the air passing through the tower has increased compared to the case without smoke injection And it increases its thermal power, which has an effect on the cycle, in the form of an increase in steam mass flow rate and production power. On the one hand, the increase in mass flow increases the production power of the steam cycle, and on the other hand, it increases the destruction of exergy, However, according to Table 4, the efficiencies of the first and second laws of thermodynamics for the state with smoke injection increase compared to the state without smoke injection for the same wind speed, which indicates a better overall cycle performance.

Table 4
First and second law of thermodynamics efficiencies

| Kind of Power Plant | Gas turbine cycle | Steam turbine cycle | Combined cycle |
|---|---|---|---|
| First law efficiency (%) No smoke injection No air injection | 33.59 | 32.26 | 51.36 |
| Second law efficiency (%) No smoke injection No air injection | 34.34 | 65.41 | 48.45 |
| First law efficiency (%) Wind speed V=20m/s No smoke injection | 33.59 | 27.04 | 48.32 |
| Second law efficiency (%) Wind speed V=20m/s No smoke injection | 34.34 | 54.83 | 45.59 |
| First law efficiency (%) Wind speed V=20m/s With smoke injection | 32.93 | 29.17 | 49.26 |

**9- Conclusion**

The overall effect of the smoke injection method on the performance of the combined cycle should be done as a result of its positive and negative effects on the gas turbine cycle and the steam turbine cycle, respectively. Based on the obtained results, the overall efficiencies of the first and second laws increase due to smoke injection for wind speeds over 3m/s, which indicates the positive performance of this method on the overall performance of the combined cycle. On the other hand, given that the exhaust smoke from the recycled steam boiler is injected into the cooling tower, And compared to the normal state that comes out of the power plant chimney, At a higher discharge height, And the amount of pollutants such as Nox, Sox, etc. will be reduced by increasing their density at levels close to the ground, which also has a positive effect from an environmental perspective.

**10- Symbols**

h Overall heat transfer coefficient
Inj Smoke injection
$K_L$ Dimensionless pressure drop coefficient
$\dot{m}$ Mass flow rate of air passing through radiators
q Heat transfer rate from radiators
$T_{ai}$ Air temperature entering the exchangers
$T_{wm}$ Average circulating water temperature
$T_{wi}$ Water temperature entering the radiators
$T_{wo}$ Water temperature leaving the radiators
$\Delta P$ Pressure drop

**Greek symbols**

$\rho$ Density

**Subtitle**

FGI Injection of hot smoke from combustion
No FGI No injection of hot smoke from combustion

**11 - References**

[1] Al- Waked R. and Behnia M., “The Performance of Natural Draft Dry Cooling Tower”, under Crosswind: CFD Study, International Journal of Energy Resource, Vol. 28, pp. 147-161, 2004.
[2] Ghaffari S., Golneshan A. and Mokhtarpoor R., “3D Nurnerical Analysis of The Performance of An NDDCT with Windbreak Walls”, Under Various Crosswind Velocities and Directions, 2007 Conference on Applications and Design in Mechanical Engineering, Kangar, Perlis, Malaysia, 2007.
[3] Jahangiri A. and Rahmani F., “Power production limitations due to the environmental effects on the thermal effectiveness of NDDCT in an operating Powe plant”,Applied Thermal Engineering, Vol. 141, pp. 444-455,2018.
[4] Eldre T.V., Benton D. J.and Hodgson J.W., “An Investigation of the Effects of Flue Gas Injection on Natural Draft Cooling Tower Performance”, Journal of Engineering For Gas Turbine and Power, Vol. 119, pp. 478-484, 1997.
[5] Cooper j., Grindle E. and Lawson R., “Improving Natural Draft Cooling Tower Performance With Heat Injection”, International Joint Power Generation Conference, Phoenix, AZ, USA, 2002.
[7] Jahangiri A. and Golneshan A. A., “Feasibility Study of the Thermal Performance Improvement of Natural Draft Dry Cooling Towers due to Flue Gas Injection”, World Applied Science Journal, Vol. 12, No. 4, pp.568-675, 2011.
[8] Jahangiri A. and Golneshan A. A., “Performance Improvement of Heller Cooling Tower under

Crosswind at Different Angles toward Towers Row Direction", 20th Annual International Conference on Mechanical Engineering- ISME2012, Shiraz University, Shiraz, Iran, 2012.

[9] Schlichting H. and Kestin J., "Boundary- layer theory.", 7th edn. McGraw-Hill, New York, 2000.