CFD ANALYSIS OF COOLING TOWER WITH FLUENT SOLVER

A Major Project Report Submitted

In Partial Fulfillment Of The Requirements For The Award Of The Degree

Of

MASTER OF TECHNOLOGY (Thermal Engineering)

Submitted By

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DECLARATION

I hereby declare that the work presented in this thesis is solely my own Work and that to the best of my knowledge, the work is original except where otherwise indicated by reference to other authors or works. No part of this work has been submitted for any other degree or diploma.

GIRI BHUSHAN SHARMA

Signature-

Date-

CERTIFICATE

This is to certify that the Major project entitled "**CFD Analysis of cooling tower With Fluent Solver"** which is being submitted by Giri Bhushan Sharma, is the authentic record of student's own work carried out by him under our guidance and supervision for partial fulfillment of the award of the degree of Master of Technology (Thermal Engineering), Department of Mechanical Engineering, Delhi Technological University, Delhi.

The matter embodied in this project has not been submitted for the award of any other degree/diploma.

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I would also like to take this opportunity to present my sincere regards to my teachers for their kind support and encouragement.

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ABSTRACT

A Cooling tower cools the working fluid using the principle of vaporization and sensible heat transfer. In this project the effect of design variables on Natural Draft Wet Cooling Tower has been observed using CFD analysis.

The aim of the current work is to analyze the cooling tower and to observe that how the cooling range of tower depends on the various design parameters. The dependency of cooling range on fills design, rain zone height, air temperature and flow rate has been observed and conceptualized. This work also aims at determining the optimum fill height, optimum rain zone height for a design specific requirement.

The problem has been solved in Discrete Phase Model using Lagrangian Particle Tracking and enabling the Stochastic Model with coupled heat and mass transfer and unsteady particle tracking assuming droplet collision and droplet breakup.

The results shows that the cooling range increases as the fill height and the rain zone height is increased but there is more strong dependency on fill height rather than rain zone height. It is also observed that the range of the cooling tower increases as the flow rate of water is decreased. Its variation is observed and recorded in FLUENT 6. Theoretically it is observed and it is also clear from FLUENT 6 results that for a lower temperature the saturation pressure of water is also comparatively lower and so the driving force for the evaporation i.e. the difference of the saturation pressure and vapor pressure is also lower and so is the rate of evaporation. Hence a lower cooling is observed in rain zone for a higher depth of fills.

The most of the factors affecting the cooling range are analyzed, recorded and compared for different sizes of the rain zone, different heights of fills, different mass flow rate, variable air temperature and an effort has been made for the optimization of the cooling tower.

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Fig: 5.35-Cooling contribution of different zones for variable air temperature

1. INTRODUCTION

1.1 BASIC HEAT TRANSFER MECHANISM IN COOLING TOWER-

Cooling tower is a structure that is used to cool the water by means of evaporation and sensible heat transfer. The cooling towers are used in process industries and power plants. In power plants heat is rejected from the cycle water at constant temperature. It happens in the condenser but the condenser water gets itself hot. So this hot water is sprayed through nozzles in the cooling tower. This spray has two advantages. First the surface to volume ratio increases so that good heat transfer occurs from nozzle droplets and second is that the water is almost homogeneously distributed. As the water evaporates if the saturation temperature of water differs from the vapor pressure of the water in air and this happens until the saturation pressure of water and vapor pressure of water in air are equal. As some water evaporates its temperature goes down because it takes latent heat from itself for evaporation. So the corresponding saturation pressure also decreases. The result is that the difference of saturation pressure and vapor pressure also decreases and so is the rate of evaporation. This happens until both the pressures are equal. So here an important conclusion may be drawn which is further verified from the results that the rate of evaporation decreases as the water comes down the cooling tower.

For evaporative cooling

$P_{sat,water} > P_{vapor\ pressure\ of\ water\ in\ air}$

1.2 TYPES OF COOLING TOWER-

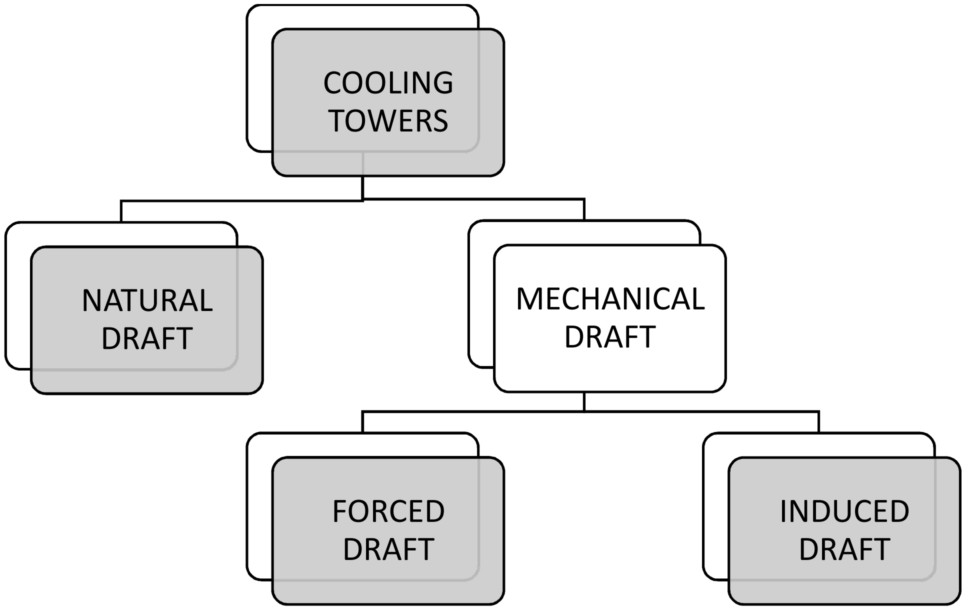

Fig- 1.1 Types of cooling tower

1.2.1 Natural Draft Cooling Towers-

- Hot air moves through tower
- Fresh cool air is drawn into the tower from bottom
- No fan required
- Concrete tower <200 m
- Used for large heat duties

1.2.2 Mechanical Draft Cooling Towers

- Forced draft
- Induced draft cross flow
- Induced draft counter flow

- Air blown through tower by centrifugal fan at air inlet
- Advantages: suited for high air resistance & fans are relatively quiet
- Disadvantages: recirculation due to high air-entry and low air-exit velocities

1.3 APPLICATIONS

HEATING VENTILATION AIR CONDITIONING (HVAC)

An HVAC (heating, ventilating, and air conditioning) cooling tower is used to dispose of ("reject") unwanted heat from a chiller. Water-cooled chillers are normally more energy efficient than air-cooled chillers due to heat rejection to tower water at or near wet-bulb temperatures. Air-cooled chillers must reject heat at the higher dry-bulb temperature, and thus have a lower average reverse-Carnot cycle effectiveness. Large office buildings, hospitals, and schools typically use one or more cooling towers as part of their air conditioning systems. Generally, industrial cooling towers are much larger than HVAC towers.

POWER PLANT AND OTHER INDUSTRIAL APPLICATIONS

Industrial cooling towers can be used to remove heat from various sources such as machinery or heated process material. The primary use of large, industrial cooling towers is to remove the heat absorbed in the circulating cooling water systems used in power plants, petroleum refineries, petrochemical plants, natural gas processing plants, food processing plants, semi-conductor plants, and for other industrial facilities such as in condensers of distillation columns, for cooling liquid in crystallization, etc. The circulation rate of cooling water in a typical 700 MW coal-fired power plant with a cooling tower amounts to about 71,600 cubic meters an hour and the circulating water requires a supply water make-up rate of perhaps 5 percent (i.e., 3,600 cubic meters an hour).

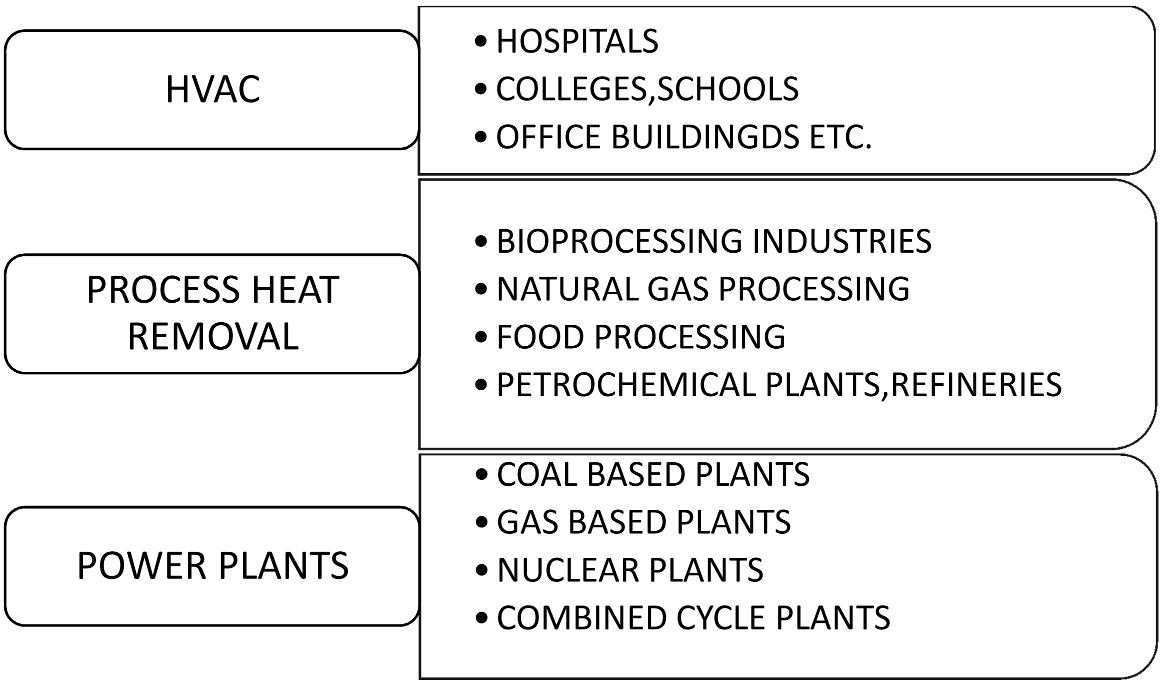

Fig- 1.2: Applications of cooling tower

1.4 TERMINOLOGY-

Windage or Drift – Drift is the undesirable loss of liquid water to the environment via small droplets in the leaving air stream. The water droplets carry with them chemicals and minerals and also the leaving stream has high humidity, thus impacting the surrounding environment.

DRIFT ELIMINATORS- Drift eliminators are designed on principle that if the mixture of air and water is made to change its direction then the air can do it easily but it is not so easy for water because it does have high inertia and so a flow obstruction helps to retain water however this method is not 100% water proof, but the design of different drift eliminators has helped a lot and the focus of researchers is to have a better and best drift eliminators design.

- **Make-up** — The water that must be added to the circulating water system in order to compensate for water losses such as evaporation, drift losses etc.
- **Approach** — The approach is the difference in temperature between the cooled-water temperature and the entering-air wet bulb temperature (t_{wb}). Since the cooling towers are based on the principles of evaporative cooling, the maximum cooling tower efficiency depends on the wet bulb temperature of the air. The wet-bulb temperature is a type of temperature measurement that reflects the physical properties of a system with a mixture of a gas and a vapor, usually air and water vapor.

Approach (°C) = CW outlet temp – Wet bulb temp

So a low approach is desirable

- **Range** — The range is the temperature difference between the warm water inlet and cooled water exit.

Range (°C) = CW inlet temp – CW outlet temp

So high range means a good performance.

Effectiveness- Cooling tower effectiveness is the ratio between the range and the ideal range (in percentage), i.e. difference between cooling water inlet temperature and ambient wet bulb temperature

Effectiveness = Range / (Range + Approach)

Effectiveness (%) = 100 x (CW temp – CW out temp) / (CW in temp – WB temp)

Cooling Capacity- Cooling capacity is the heat rejected in KCal/hr or tons of refrigeration (TR), given as product of mass flow rate of water, specific heat and temperature difference.

Hot water is sprayed over the fill material. The spray zone can account for as much as 25% of 1he total heat transfer in a tower. It is very important that the water is distributed uniformly over the fill. Misdistribution of liquid flow is often cited as a cause of reduced performance in packed towers.

2. LITERATURE REVIEW

Alok Singh et al. [1] have developed a model in commercial code FLUENT. They have done the analysis of a natural draft wet cooling tower using a two dimensional CFD approach. This model aims at determining the heat and mass transfer from water to air. They have used the Eularian multiphase model and RNG K-ε model to simulate the flow and turbulence modelling of multiphase flow respectively. They have reported a low value of density along the axis of cooling tower. it's higher value is found near the wall. Highest value of thermal conductivity is found near the axis. They have found the stream function to be linearly constant for axis.

G. Gan et al. [2] have applied CFD to determine the performance of closed wet cooling towers according to their cooling capacity and pressure loss. They have compared their results with experimental observations for a large industrial as well as prototype cooling tower. They have shown that CFD can be used for determining the performance, pressure loss and optimum design of cooling tower. They have also suggested that for good results and simplifications in CFD the varying heat flux should be used instead of constant heat flux.

Daeho Kang et al. [3] have determined the unique air flow characteristics in a passive down draft evaporative cooling tower. They have analyzed the turbulent and wall bounded flow. The study was focused at understanding a viable solution for improving sustainability in buildings. They have reported that it is difficult to maintain a constant performance for a passive down draft evaporative cooling tower.

H.C.R. Reuter et al. [4] have investigated the effects of cooling tower inlet design on inlet viscous flow losses using ANSYS-FLUENT. They have compared the axial velocity profile data, tower inlet losses with the experimental results. Further they have used the same CFD model for determining the effect of the inertia forces and viscous forces, shell wall thickness and shell wall inclination on the air flow pattern. Finally they have developed simple correlations for determining the cooling tower inlet losses. They have reached at a conclusion that the inlet diameter to height ratio has a major impact on inlet losses.

Robert N. Meroney [5] has used a CFD code to predict the plume rise, surface concentration, plume centerline and surface drift deposition using Lagrangian prediction of gravity driven flows. He has considered stochastic trajectory of droplets.

Rafat Al Waked et al. [6] have investigated the effect of operating conditions and crosswind conditions for a 3 dimensional natural draft wet cooling tower using FLUENT and have utilized the standard K-ε turbulence model. They considered Eularian approach for air phase and Lagrangian approach for water phase. They have also investigated the effect of droplet diameter, no. of nozzles and no. of tracks per nozzle. They have reported that droplet diameter has the most significant improvement on the thermal performance of the cooling tower.

N. Williiamson et al. [7] have developed one dimensional and two dimensional CFD models and compared them under the design variables. They have reported a difference of less than 2% between the results of one dimensional model and two dimensional model. The difference between the tower range is found to be less than .4% in most cases.

Jorge Facao et al. [8] have focussed on the understanding on heat and mass transfer mechanism involved and to check the possibility of using the CFD code FLUENT for simulating mass and heat transfer phenomena in an indirect cooling tower. They found that the mass transfer coefficient obtained through CFD code FLUENT was close to experimental correlation, specially at higher flow rate.

Blas Zamora et al. [9] have numerically simulated the air water droplet motion through three different types of drift eliminators using Ansys-Fluent. They determined the coefficient of pressure drop and the droplet collection efficiency. They concluded that the effect of turbulence model on droplet collection efficiency deserves a most detailed and elaborative analysis. They reported that the droplet turbulent dispersion has a major impact on the collection efficiency.

Bilal A Qureshi et al. [10] have solved the cooling zone using engineering equation solver software. They compared the results with experimental data. They focussed on the fouling of fills and presented his fouling model in terms of normalized fill performance index. They found fouling to be a major source of degradation of cooling tower performance.

Nenad Milosavljevic et al. [11] have derived a mathematical model for a counter flow wet cooling tower which is based on one dimensional heat and mass balance equations using the measured heat transfer coefficients. They used the model to determine the performance characteristics of counter flow wet cooling tower using the developed mathematical model.

N.J. Williamson [12] has focussed his work on the modeling, design and optimization of natural draft wet cooling tower. He conducted a detailed analysis of heat and mass transfer. He observed that water mass flow rate and droplet size has major impact on heat transfer among all the parameters considered. He used the observations for optimization of the tower using the developed modeling.

M. Zunaid et al. [13] have focussed their work on fresh water production using humidification and de-humidification. They developed a model in MATLAB for solving the basic governing equations. They reached at many vital conclusions and reported that the fresh water production rate increases if air mass flow rate or/and air temperature is increased. They also showed that the decrease in water temperature also significantly improves the fresh water production rate.

Hanno Carl Rudolf Reuter [14] has analyzed the effect of structural parameters and air flow resistance on performance of cooling tower using FLUENT. He also investigated the effect of rain zone drop size distribution, water loading. He suggested that the performance of a cooling tower can be improved by making protruded roundings at inlet, reducing droplet size and by reducing air inlet height.

D. J. Viljoen [15] studied the effect of water distribution, drop size distribution and heat transfer on the thermal performance of cooling tower using FLUENT.

He also developed a model to predict the path of droplets. He tested two medium pressure nozzle and two low pressure nozzles. He reported the collision of water droplets has not major impact on water distribution pattern.

D.G. Kroger [16] has performed the CFD analysis for rain zone and spray zone .He showed the relative contribution of cooling zones. He concluded that rain zone can provide up to 30% cooling and spray zone can provide up to 5-10% of overall cooling. He developed one dimensional, two dimensional and three dimensional cooling towers and has found the results of all models in close proximity. He has also developed empirical correlations for flow/viscous loses.

D. Radosavljevic [17] has developed an axisymmetric and three dimensional CFD modal of a natural draft wet cooling tower. He has used the turbulence model and Lagrangian model for discreet phase tracking and found his results in closed approximation to that of experimental observations .He also measured the heat and mass transfer coefficients in the developed CFD model. He analyzed the effect of cross wind conditions on the cooling tower performance.

H. Lowe et al. [18] have worked on heat transfer and pressure drop in cooling tower .They found transfer characteristics for a fine spray system in terms of spray pressure and height through which the droplet falls. He varied the spray head from 1.2 - 3.6 meter and took the sauter mean diameter in the range of .9 – 1.28 milimeter. He showed that mean diameter of droplet increases as the droplets increases as the droplet falls through spray zone.

M.N.A. Hawlader et al. [19] has done the numerical study of the thermal-hydraulic performance of evaporative natural draft cooling tower. He used one dimensional Lagrange particle tracking involving the coupling of heat, mass and momentum. He showed that the rain zone pressure distribution in the tower is nearly uniform.

Suresh Kumar [20] showed the variance in droplet size distribution with respect to different projection angles. He also observed the variation of projection angle as a function of air inlet velocity.

3. CFD MODEL AND BASIC GOVERNING EQUATIONS

3.1 BASIC GOVERNING EQUATIONS

3.1.1 MASS CONSERVATION EQUATION (CONTINUITY EQUATION)

The equation for conservation of mass, or continuity equation, can be written as follows:

$$\frac{\partial p}{\partial t} + \nabla.(\rho \vec{v}) = S_m \qquad \text{……………….3.1}$$

Equation is the general form of the mass conservation equation and is valid for incompressible as well as compressible flows. The source S_m is the mass added to the continuous phase from the dispersed second phase (e.g., due to vaporization of liquid droplets) and any user-defined sources.

For 2D ax symmetric geometries, the continuity equation is given by

$$\frac{\partial p}{\partial t} + \frac{\partial}{\partial x}(\rho v_x) + \frac{\partial}{\partial r}(\rho v_r) = S_m \qquad \text{…………………3.2}$$

Where x is the axial coordinate, r is the radial coordinate, v_x is the axial velocity, and v_r is the radial velocity.

3.1.2 MOMENTUM CONSERVATION EQUATIONS

Conservation of momentum in an inertial (non-accelerating) reference frame

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla.(\rho \vec{v}\vec{v}) = -\nabla p + \nabla.(\bar{\bar{\tau}}) + \rho \vec{g} + \vec{F} \qquad \text{………………………..3.3}$$

Where p is the static pressure, τ is the stress tensor (described below), and ρg and F are the gravitational body force and external body forces (e.g., that arise from interaction with the dispersed phase), respectively. F also contains other model-dependent source terms such as porous-media and user-defined sources.

3.1.3 ENERGY EQUATION

General energy equation is as follows;

$$\frac{\partial}{\partial t}(\rho E) + \Delta.(\vec{v}(\rho E + p)) = \nabla.(k_{eff}\nabla T - \sum_j h_j \vec{J}_j + (\overline{\overline{\tau}}_{eff}.\vec{v})) + S_h \quad \text{..........3.4}$$

Where k_{eff} is the effective conductivity defined according to the turbulence model and $\vec{J}_j$ is the diffusion flux of species j. The first three terms on the right-hand side of Equation represent energy transfer due to conduction, species diffusion, and viscous dissipation, respectively. S_h Includes the heat of chemical reaction, and any other volumetric heat sources is defined.

3.2 ASSUMPTIONS-

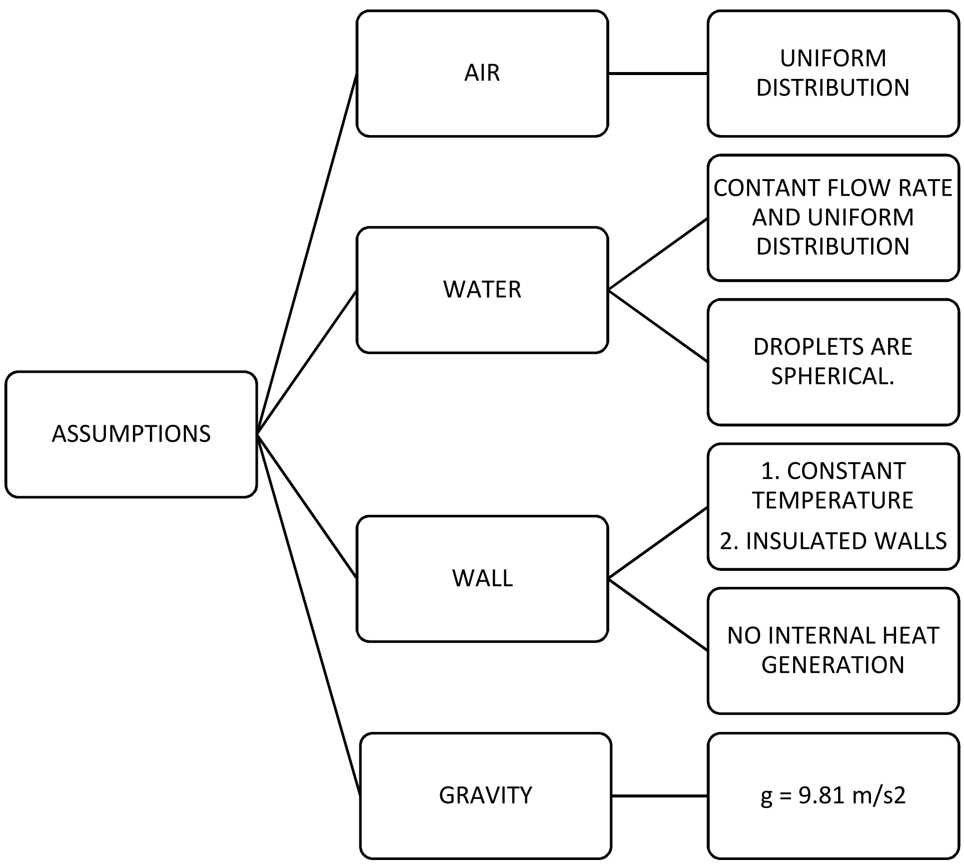

Fig-3.1: Assumptions

The above assumptions were considered for the purpose of simplification and in accordance with the problem.

3.3 TURBULENCE MODELLING-

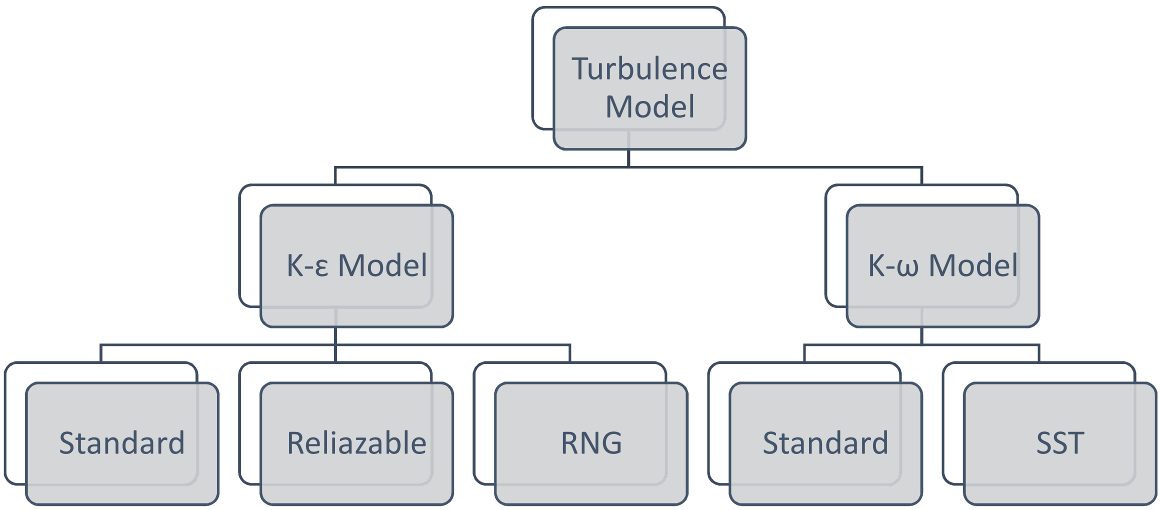

Fig-3.2: Turbulence Models

Turbulent Flows are characterized by fluctuating velocity fields. These fluctuations mix transported quantities such as momentum, energy, and species concentration, and cause the transported quantities to fluctuate as well. Since these fluctuations can be of small scale and high frequency, they are too computationally expensive to simulate directly in practical engineering calculations. Instead, the instantaneous (exact) governing equations can be time-averaged, ensemble-averaged, or otherwise manipulated to remove the small scales, resulting in a modified set of equations that are computationally less expensive to solve. However, the modified equations contain additional unknown variables, and turbulence models are needed to determine these variables in terms of known quantities.

Choosing a Turbulence Model

It is an unfortunate fact that no single turbulence model is universally accepted as being superior for all classes of problems. The choice of turbulence model will depend on considerations such as the physics encompassed in the flow, the established practice for a specific class of problem, the level of accuracy required, the available computational resources, and the amount of time available for the simulation.

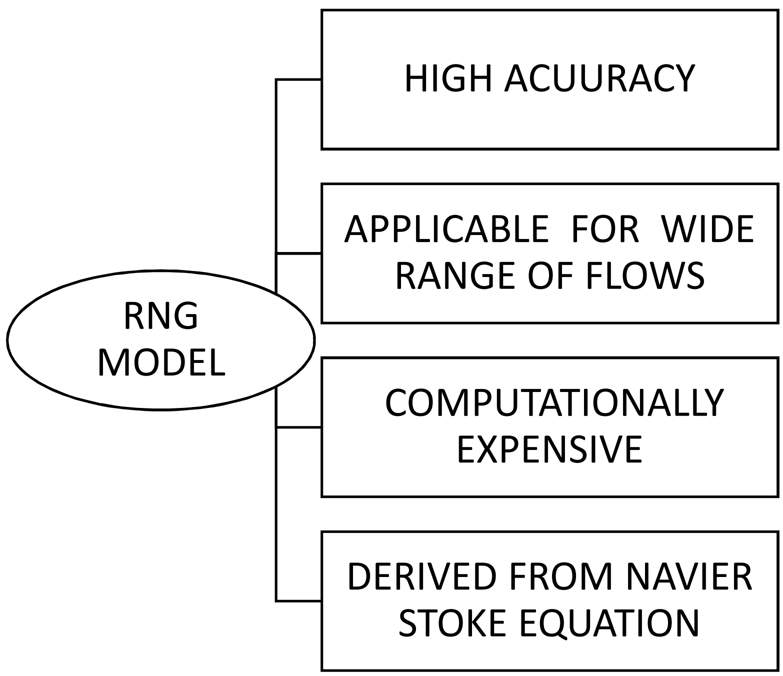

Fig-3.3: RNG k- ε model

In my project problem I have used RNG k- ε model for simulating the problem because of its inherent advantages.

3.3.1 RNG k-ε Model

The RNG k-ε model was derived using a rigorous statistical technique (called Renormalization group theory). It is similar in form to the standard k-ε model, but includes the following refinements:

1. The RNG model has an additional term in its ε equation that significantly improves the accuracy for rapidly strained flows.

2. The effect of swirl on turbulence is included in the RNG model, enhancing accuracy for swirling flows.

3. The RNG theory provides an analytical formula for turbulent Prandtl numbers, while the standard k-ε model uses user-specified, constant values.

4. While the standard k-ε model is a high-Reynolds-number model, the RNG theory provides an analytically-derived differential formula for effective viscosity that accounts for low-Reynolds-number effects. Effective use of this feature does, however, depend on an appropriate treatment of the near-wall region.

These features make the RNG k-ε model more accurate and reliable for a wider class of flows than the standard k-ε model.

The RNG-based k-ε turbulence model is derived from the instantaneous Navier-Stokes equations, using a mathematical technique called “renormalization group" (RNG) methods.

The analytical derivation results in a model with constants different from those in the standard k-ε model, and additional terms and functions in the transport equations for k and ε.

Transport Equations for the RNG k-ε Model

The RNG k-ε model has a similar form to the standard k-ε model:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left(\alpha_k \mu_{eff} \frac{\partial k}{\partial x_j}\right) + G_k + G_b - \rho\epsilon - Y_M + S_K \qquad \ldots\ldots\ldots..3.5$$

And

$$\frac{\partial}{\partial t}(\rho \epsilon) + \frac{\partial}{\partial x_i}(\rho \epsilon u_i) = \frac{\partial}{\partial x_j}\left(\alpha_k \mu_{eff} \frac{\partial \epsilon}{\partial x_j}\right) + C_{1\epsilon}\frac{\epsilon}{k}(G_k + C_{3\epsilon}G_b) - C_{2\epsilon}\rho\frac{\epsilon^2}{k} - R_\epsilon + S_\epsilon$$

$$\ldots\ldots\ldots\ldots\ldots\ldots..3.6$$

In these equations,

G_k- represents the generation of turbulence kinetic energy due to the mean velocity gradients, calculated as Modeling Turbulent Production in the k- ϵ Models.

G_b- is the generation of turbulence kinetic energy due to buoyancy, calculated as Effects of Buoyancy on Turbulence in the k- ϵ Models.

Y_M - represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate, calculated as Effects of Compressibility on Turbulence in the k- ϵ Models.

$C_{1\epsilon}$, $C_{2\epsilon}$ and $C_{3\epsilon}$ are constants. α_k and α_ϵ are the inverse effective Prandtl numbers for k and ϵ, respectively. S_K and S_ϵ are user-defined source terms.
$C_{1\epsilon}$ = 1.42; $C_{2\epsilon}$ = 1.68

3.4 FLUENT SOLUTION APPROACH (HOW DOES IT SOLVE THE PROBLEM ?)-

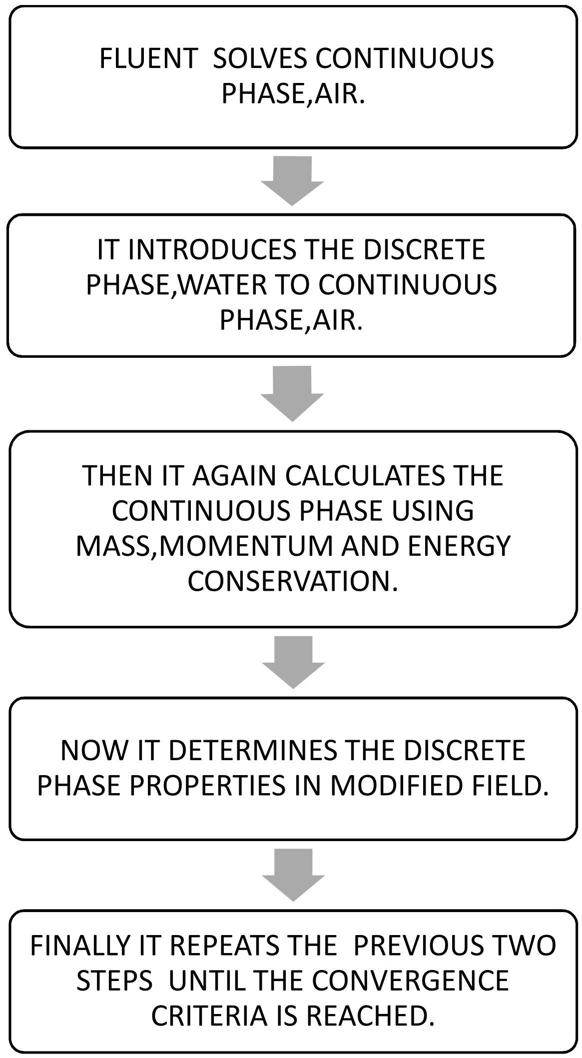

Fig -3.4: Fluent solution approach

1. First it solves the continuous field which is air.
2. Then it introduces the secondary phase to the continuous phase i.e. air.
3. Then it calculates the continuous flow field using the basic governing equations.
4. Then it determines the discrete phase properties in the modified field.

5. Now the step 3 and step 4 are repeated until the convergence criteria is satisfied.

This is how the FLUENT 6 solves the problem in the present case.

3.5 DISCRETE PHASE MODELLING-

The water was treated as discrete phase and air as primary phase. The two way turbulence coupling is used because there is a strong dependency between the phases present i.e. water and air. The discrete phase water was made to interact with the air, which is the continuous phase. The discrete phase was updated after 10 iterations for the air (continuous phase).The water particles were treated in a unsteady manner. The time step used was .1 second. To take into account the variation of turbulent quantities two way turbulence coupling was used.

To ensure the uniform distribution of water droplets the surface injection was used. The droplet collision and droplet breakup was considered to realize the problem in a practical way. The discrete phase droplets were injected at a constant mass flux. For modeling of the particle turbulent dispersion stochastic tracking approach was used.

The flow was simulated using the procedure described above**.**

EQUATIONS OF MOTION FOR PARTICLES

The trajectory of a discrete phase particle (or droplet or bubble) by integrating the force balance on the particle, which can be written in a Lagrangian reference frame. This force balance equates the particle inertia with the forces acting on the particle, and can be written (for the x direction in Cartesian coordinates) as:

$$\frac{du_p}{dt} = F_D(u - u_p) + \frac{g_x(\rho_p - \rho)}{\rho_p} + F_x$$ 3.7

Where, the drag force per unit particle mass is $F_D(u - u_p)$ and

$$F_D = \frac{18\mu}{\rho_p d_p^2} * \frac{C_D \mathrm{Re}}{24}$$ 3.8

Where, u is the fluid phase velocity, u_p is the particle velocity, μ is the molecular viscosity of the fluid, ρ is the fluid density, ρ_p is the density of the particle, and d_p is the particle diameter. C_D is discharge coefficient and Re is the Reynolds number.

Heat and Mass Transfer Calculations

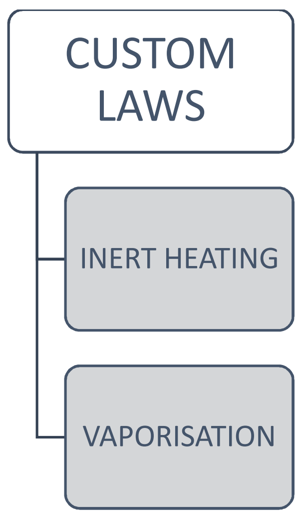

Fig- 3.5: Custom law

3.6 PROCEDURE AT A GLANCE-

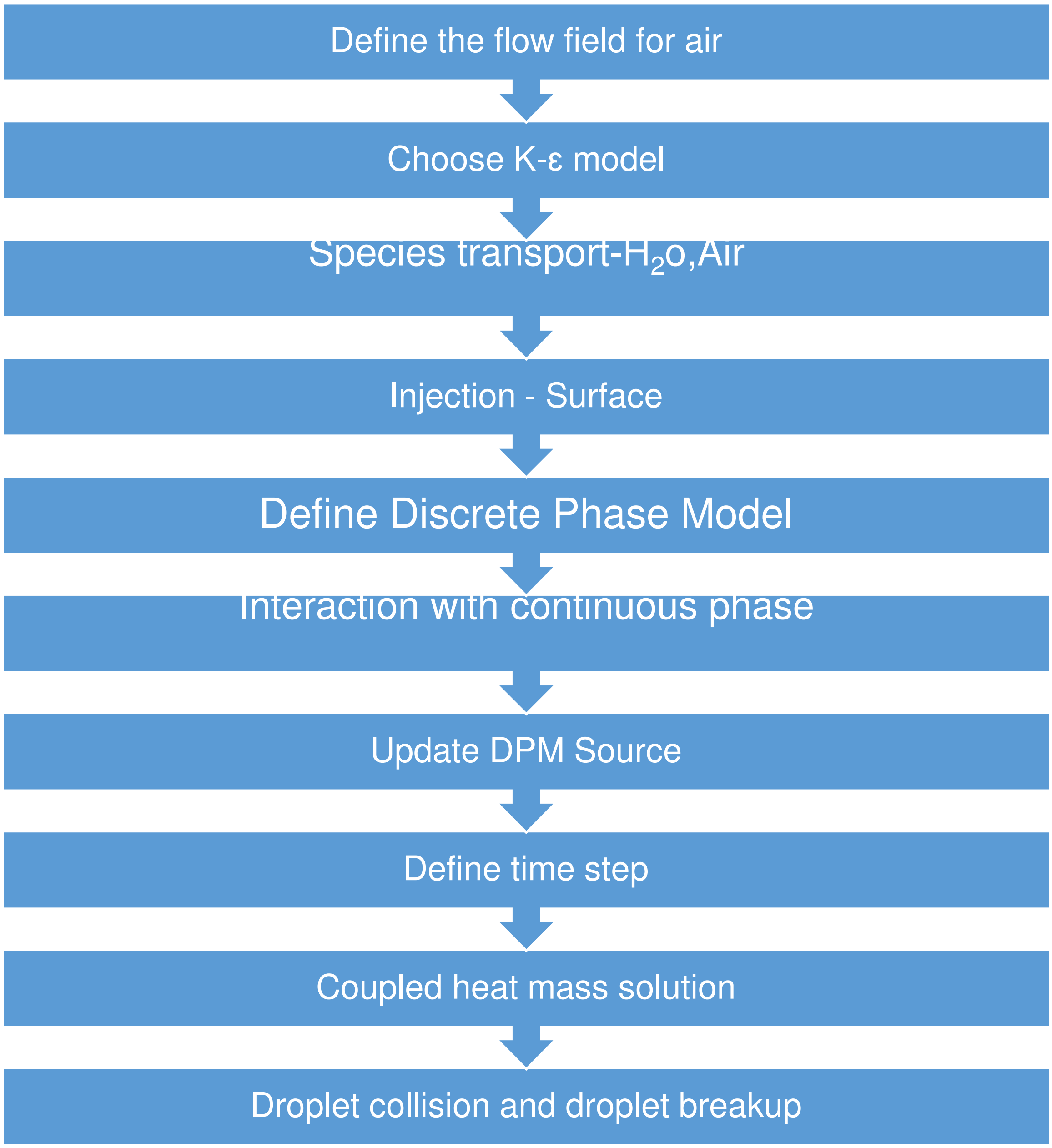

Fig-3.6: Procedure at a glance

3.7PROCESS FLOW CHART

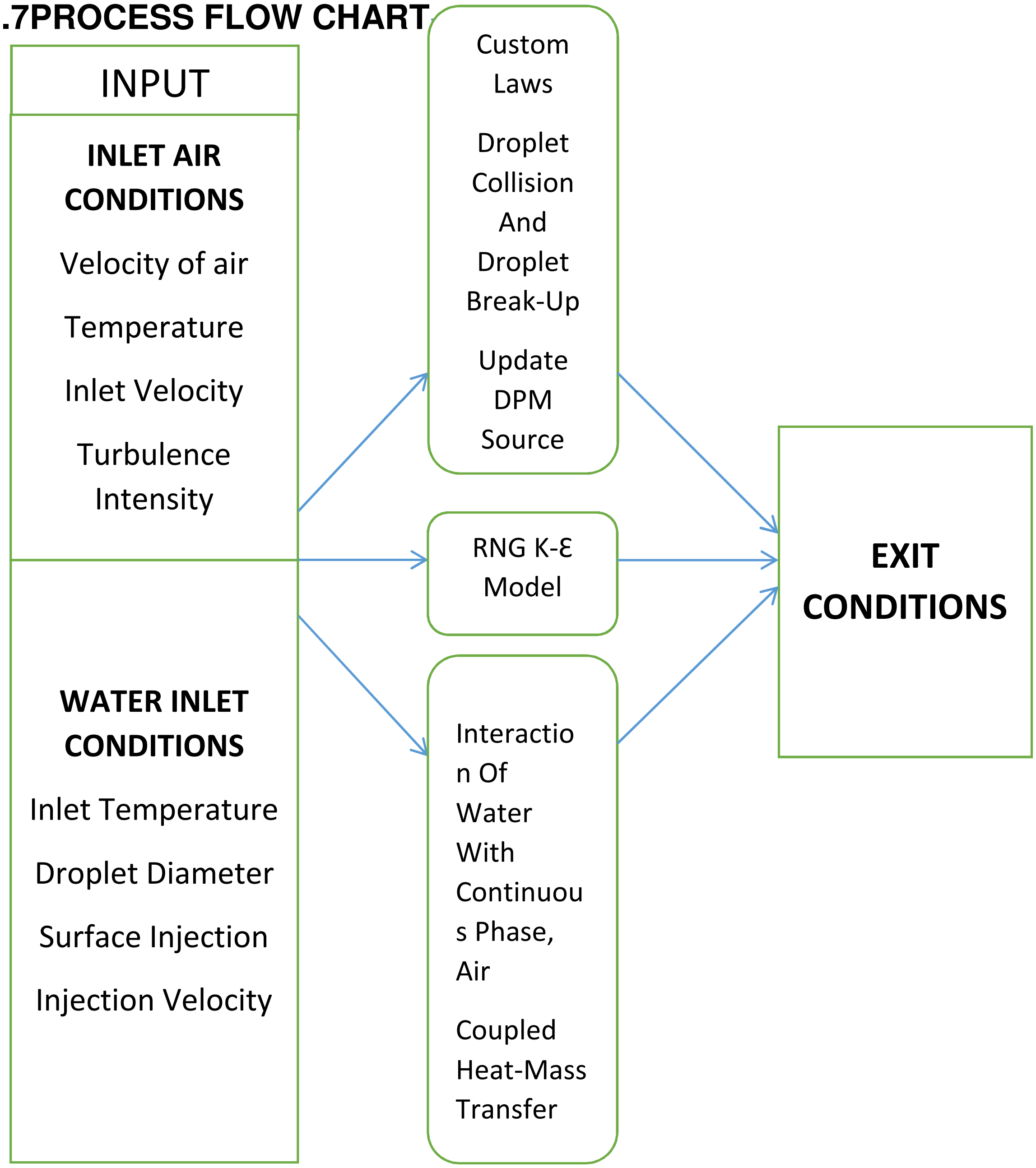

Fig-3.7: Process Flow Chart

4. 2 DIMENSIONAL NDWCT MODEL

4.1 REFERENCE FOR VALIDATION

In the work presented I have taken a reference from the work carried out by N. Williamson, M. Behnia, S. Armfield in the research paper titled “Comparison of a 2D axisymmetric CFD model of a natural draft wet cooling tower and a 1D model”.

The cooling tower geometry and other parameters were taken from the same. The work was verified and extended to include the effect of fill depth, rain zone, flow rate and droplet size. The droplets were injected using discrete phase model. The air is taken as continuous phase and water droplets as secondary phase. The droplets were modelled using Lagrange method of particle tracking.

4.2 REFERENCE PARAMETERS-

Tower Height	-	131 m.
Base diameter	-	98 m.
Flow rate	-	15000 kg/sec
Water inlet temperature	-	313 K
Tower inlet height	-	8.577 m.
Fill depth	-	1 m.
Ambient inlet Temperature	-	295 K

The droplet size is considered to be uniform having a diameter of 2.8 mm. with initial radial velocity varying from -6.3 to 6.3 m/s. The ambient air humidity was taken to be 55%.The inlet turbulence intensity was assumed 5%.

4.3 SOLUTION PROCEDURE-

1. The ambient air is made to flow in the solver FLUENT 6 at its ambient temperature and pressure which are assumed to be 295K and 101325 Pascal respectively. The turbulence intensity in the air is assumed 5%.
The solver used in air analysis is pressure based solver which is computationally beneficial and efficient for incompressible flows. The Green-Gauss cell based gradient option is used in the analysis. The gravitational acceleration is taken as 9.81m/s^2.standard k-epsilon (2-eqn) viscous model is used.

2. The species transport function is enabled in Fluent 6 and the species transport is specified for the air and water.

3. The water is injected using the custom laws. Two custom laws used are inert heating and vaporization. Now the temperature, mass flow rate and other variables are specified. The Lagrange particle tracking is used to track the droplets .The discrete random walk model is used under stochastic tracking.

4. Now the water interaction with air is enabled and unsteady particle tracking is used. Two way turbulence coupling and coupled heat and mass transfer is used in the analysis .Automated tracking scheme is also enabled .To enhance the accuracy of the solution the droplet collision and droplet breakup is used.

4.4 RELAXATION PARAMETERS-

Energy	-	0.5
Mass	-	0.4
Radial Momentum	-	0.3
Axial Momentum	-	0.3
DPM Momentum Source	-	0.3

DPM Energy Source	-	0.3
DPM Mass Source	-	0.3

4.5 ACTIVATED FLUENT SOLVE CONTROL INPUT DATA-

Controls/ Solution/ Under-relaxation factors	-	Default
Controls/ Solution/ Pressure-velocity coupling	-	Simple
Controls/ Solution/ Discretization/ Pressure	-	Body force weighted
Controls/ Solution/ Discretization/ Density	-	Second order upwind
Controls/ Solution/ Discretization/ Momentum	-	Second order upwind
Controls/ Solution/ Discretization/ Turbulence	-	Second order upwind
Controls/ Solution/ Discretization/ Turbulence dissipation rate	-	Second order upwind
Controls/ Solution/ Discretization/ H2O	-	Second order upwind
Controls/ Solution/ Discretization/ Energy	-	Second order upwind

4.6 ACTIVATED FLUENT DPM INJECTION INPUT DATA-

Injection type	Surface
Release from surface	Rain zone inlet
Particle type	Droplet
Material	Water-liquid
Diameter distribution	Uniform
Evaporating species	H_20

4.7 ACTIVATED FLUENT MODEL INPUT DATA-

Description	Setting	Input value
Solver	Pressure based	---
Formulation	Implicit	---
Space	Axisymmetric `	---
Time	Steady	---
Velocity formulation	Absolute	---
Gradient option	Green-Gauss cell based	---
Porous formulation	Superficial velocity	---
Multiphase/ Model	Off	---
Energy	Activated	---
Viscous/ Model	k-ε Realizable	---
Viscous/ Near-wall treatment	Non-equilibrium wall functions	---
Viscous/ Options	Full buoyancy effects	---
Species/ Model	Species transport	---
Species/ Options	Inlet diffusion	---
Species/ Options	Diffusion energy source	---
Species/ Mixture	material Mixture-template	---
Species/ Number of volumetric species	---	2
DPM/ Interaction	Interaction with continuous phase	---
DPM/ Interaction	Number of continuous phase interact ions per DPM iteration	---
DPM/ Tracking/ Tracking Parameters	Step length factor	5
DPM/ Numerics/ Options	Accuracy control tolerance	1e-9
DPM/ Numerics/ Options	Max. refinements	20
DPM/ Numerics/ Tracking	Automated/ High order scheme/	---

scheme selection	Trapezoidal	
DPM/ Numerics/ Tracking scheme selection	Automated/ Low order scheme/ Implicit	---

5. RESULTS, DISCUSSION AND CONCLUSIONS

The analysis has been done for the variable mass flow rate of the cooling tower and the cooling range has been determined for the design variables i.e. fill depth, rain zone height, air temperature and flow rate. The efficiency of the cooling tower depends on the sensible heat transfer and vaporization which in turns depends on the saturation pressure, vapor pressure and the time available for this intimate contact. These factors are the very strong function of fill depth, rain zone height, droplet diameter, base diameter and the type of flow. The major drop in temperature occurs in the fill zone because of the presence of solid boundaries. The fills walls cause the flow velocity to reduce and hence more time per unit length travel is available. The viscous and inertial resistance to flow causes a major impact on its efficiency. I have observed the variation in cooling effect for the different height of fill zone. I have also observed the variation in cooling effect for the different height of rain zone. In the results presented in my thesis I have also analyzed the effect of water mass flow rate on the cooling in rain zone and fill zone. Further the effect of air inlet temperature on the cooling in rain zone and fill zone is observed. The relative contribution of the both zones is also shown. In the work presented in this thesis the conditions are same unless otherwise specified.

5.1 THE EFFECT OF VARIABLE FILL ZONE HEIGHT ON COOLING-

The following results have been obtained for the same mass flow rate and at the same reference conditions as specified before. The mass flow rate is 15000 kg/s and the turbulence intensity is 5%.The droplet diameter in the present study is assumed uniform.

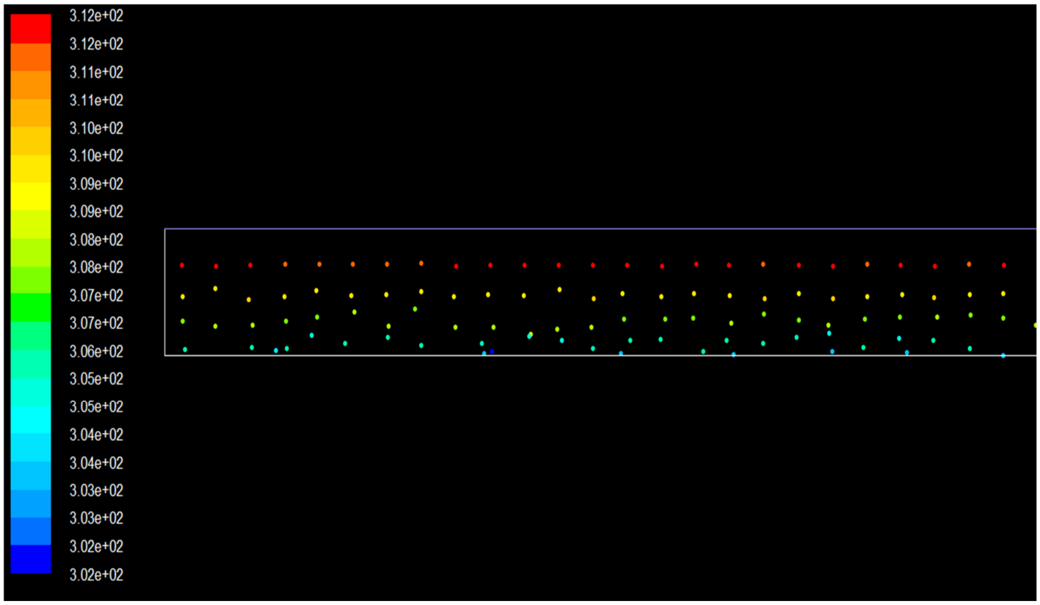

Fig: 5.1a Water temperature variation contour for .4 meter height of fill

Fig: 5.1a shows the temperature variation in the fill zone of the cooling tower having a height of .4 meter. In this picture the water temperature is decreasing from 312 K to 305.4.

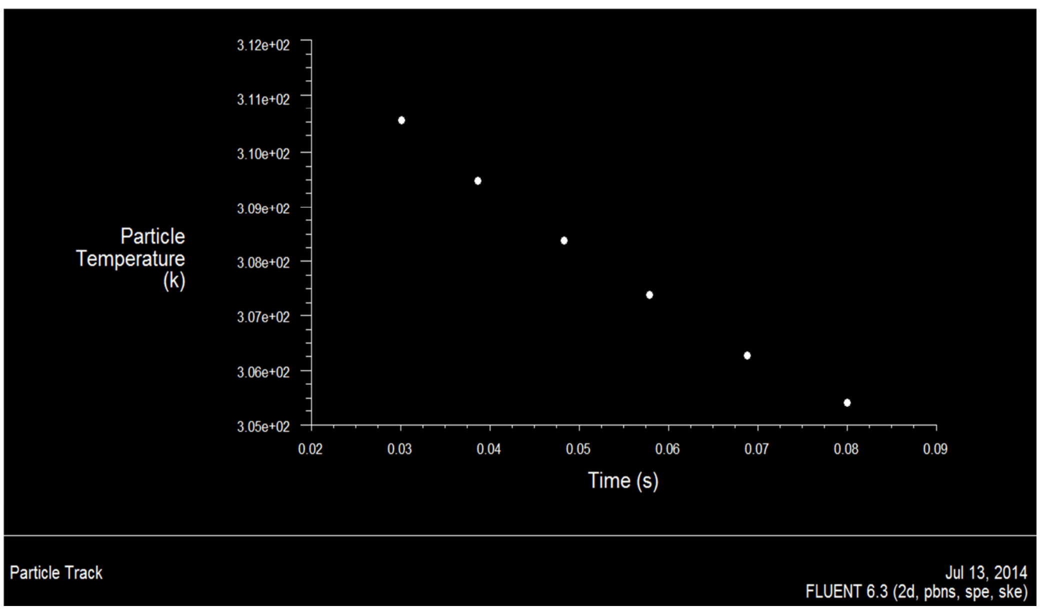

Fig: 5.1b Water temperature variation plot for .4 meter height of fill

Fig: 5.1b represents temperature vs. time variation. It shows the temperature of water is decreasing up to 305.4 K.

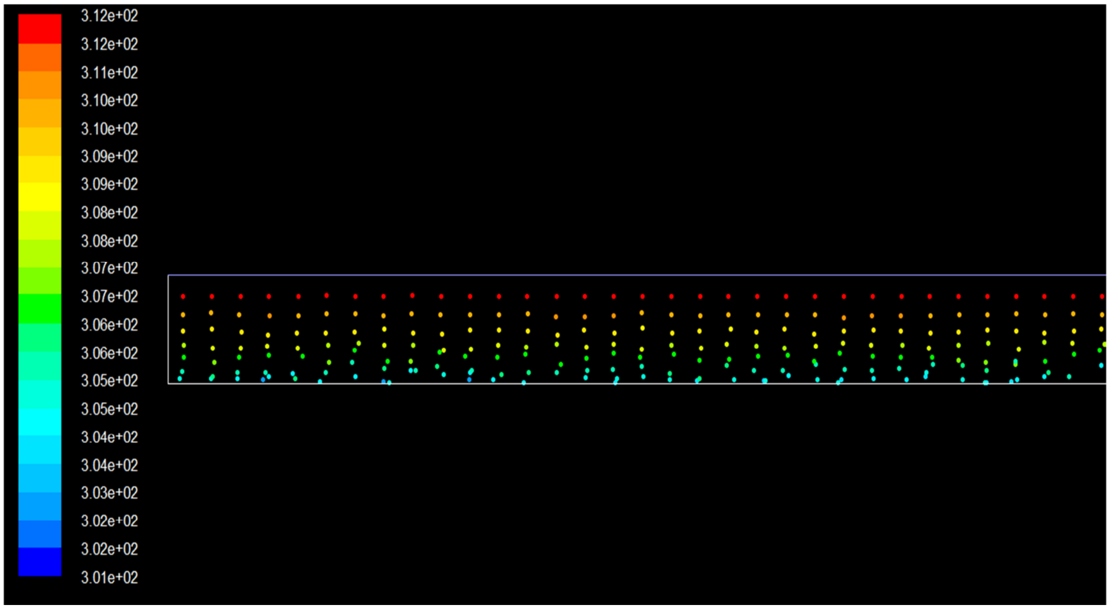

Fig: 5.2a Water temperature variation contour for .6 meter height of fill

Fig: 5.2b shows the temperature variation in the fill zone of the cooling tower having a height of .6 meter. In this picture the water temperature is decreasing from 312 K to 304.35

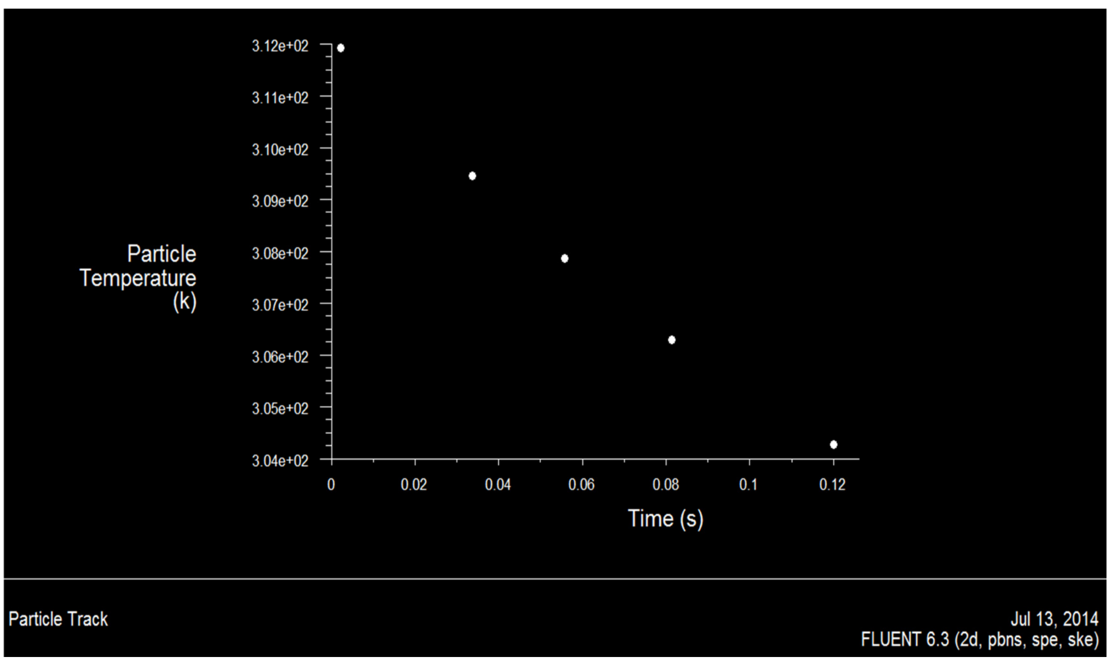

Fig: 5.2b Water temperature variation plot for .6 meter height of fill

Fig: 5.2b represents temperature vs. time variation. It shows the temperature of water is decreasing from 312 K to 304.35 K.

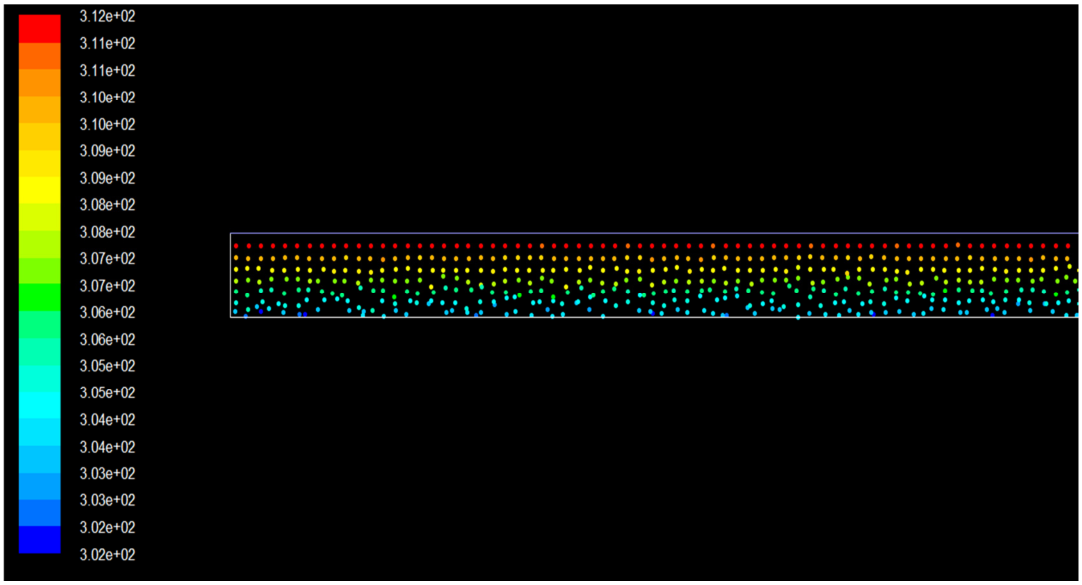

Fig: 5.3a Water temperature variation contour for .8 meter height of fill

Fig: 5.3a shows the temperature variation in the fill zone of the cooling tower having a height of .8 meter. In this picture the water temperature is decreasing from 312 K to 303.3 K.

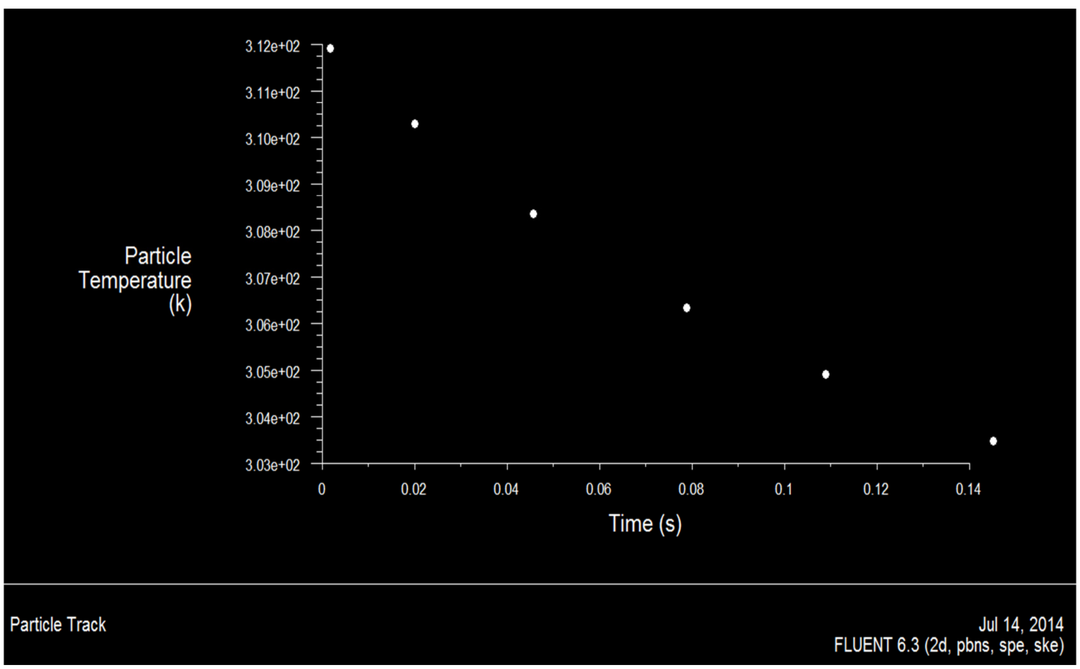

Fig: 5.3b Water temperature variation plot for .8 meter height of fill

Fig: 5.3b represents temperature vs. time variation. It shows the temperature of water is decreasing from 312 K to 303.3 K.

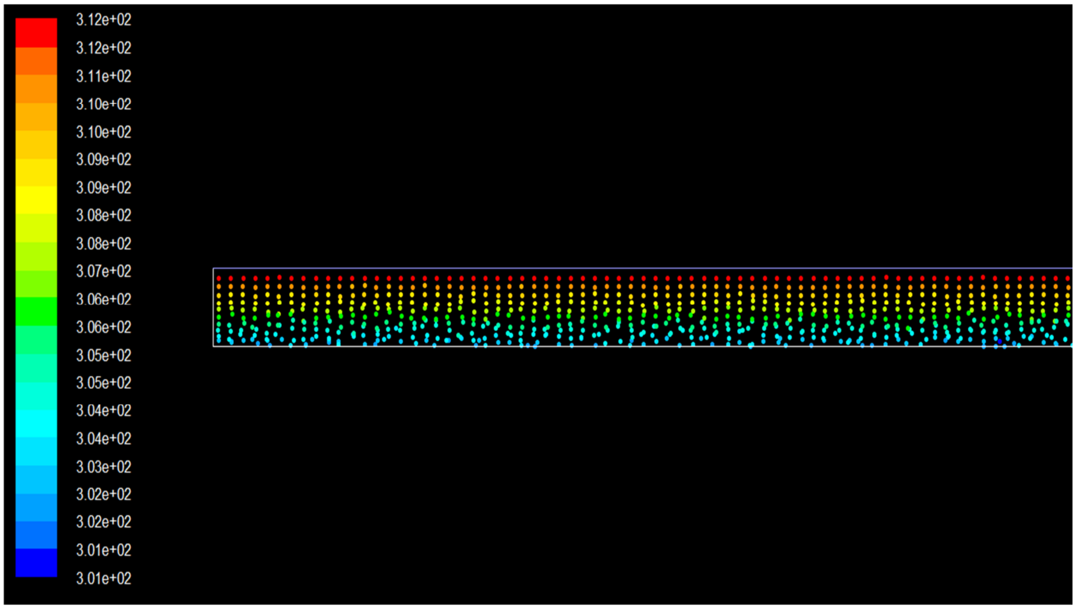

Fig: 5.4a Water temperature variation contour for 1 meter height of fill

Fig: 5.4a shows the temperature variation in the fill zone of the cooling tower having a height of 1 meter. In this picture the water temperature is decreasing from 312 K to 302.6 K.

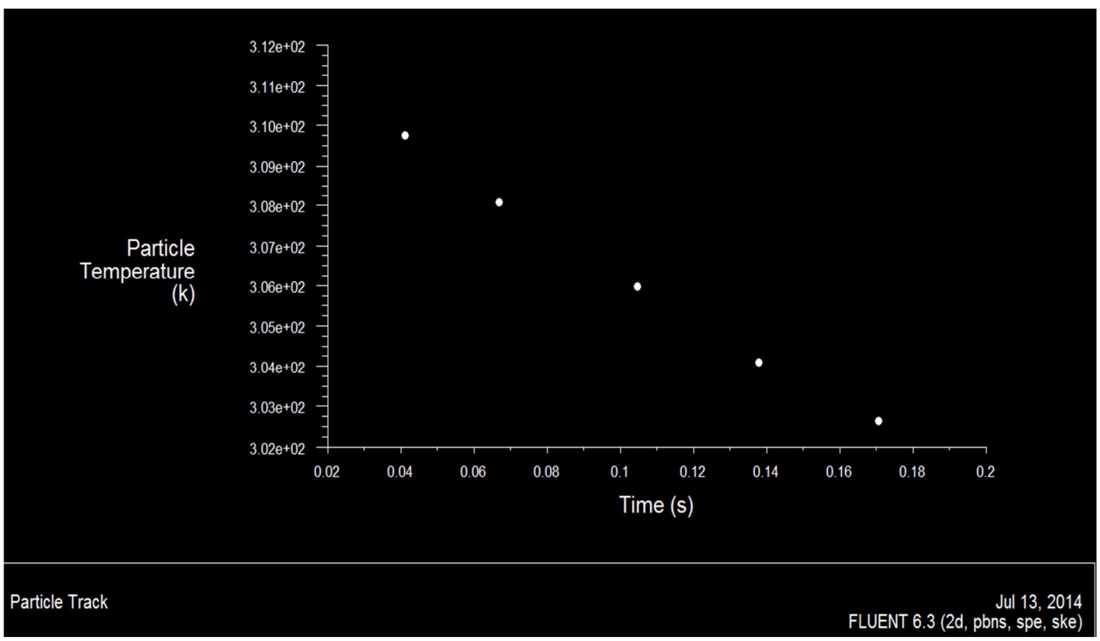

Fig: 5.4b Water temperature variation plot for 1 meter height of fill

Fig: 5.4b shows temperature vs. time variation. It shows the temperature of water is decreasing from 312 K to 302.6 K.

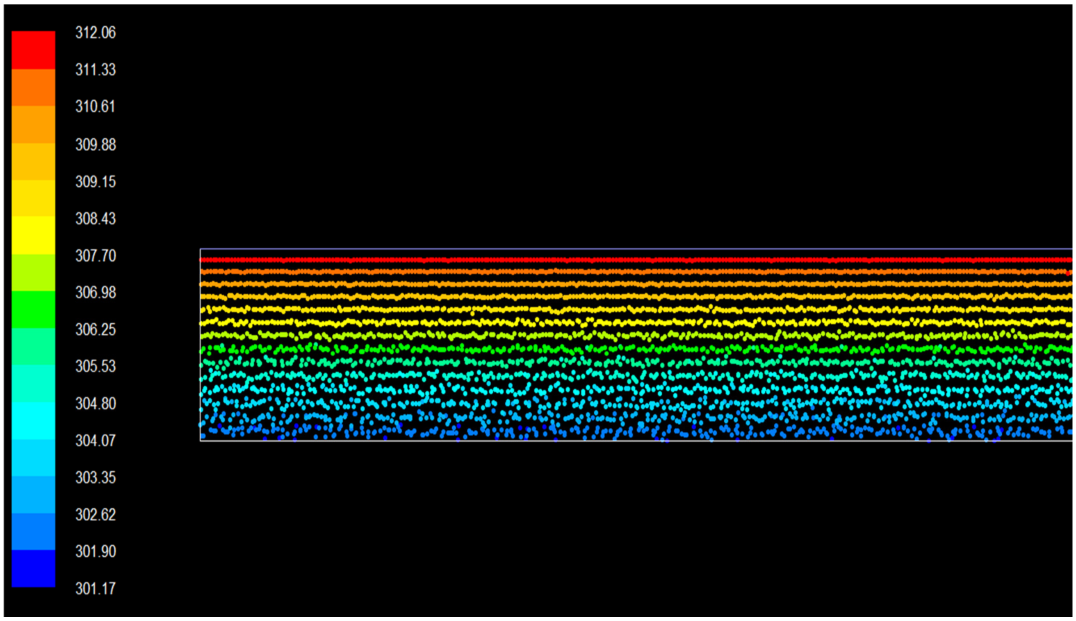

Fig: 5.5a Water temperature variation contour for 1.4 meter height of fill

Fig: 5.5a shows the temperature variation in the fill zone of the cooling tower having a height of 1.4 meter. In this picture the water temperature is decreasing from 312 K to 302 K.

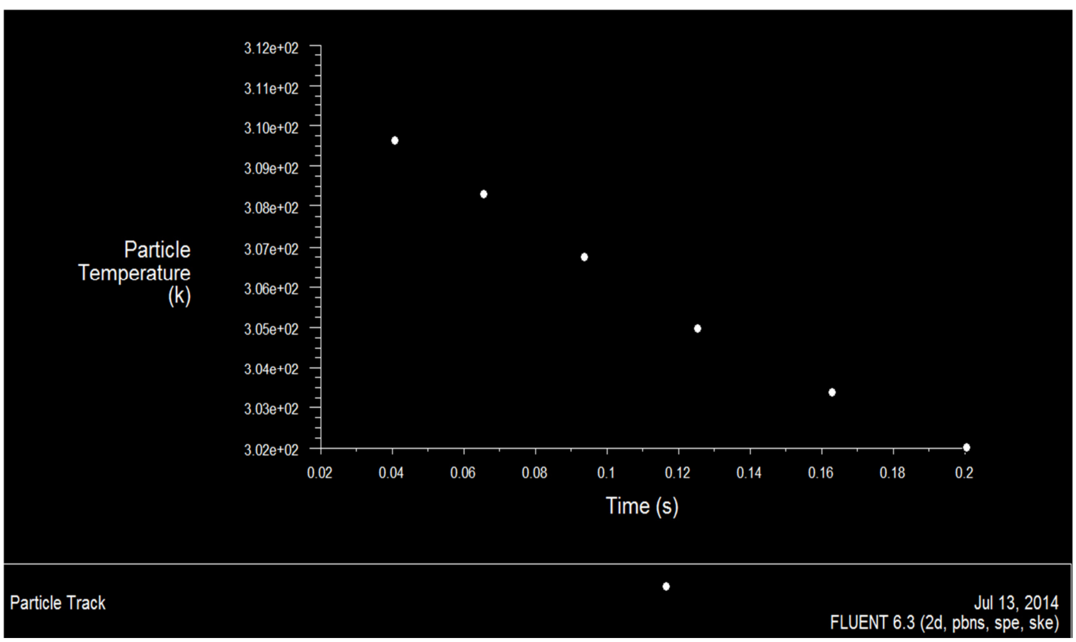

Fig: 5.5b Water temperature variation plot for 1.4 meter height of fill

Fig: 5.5b represents temperature vs. time variation. It shows the temperature of water is decreasing from 312 K to 302 K.

Table 6.1- Effect of fills depth

Sr. No.	H_{fill}	$T_{w,i}$	$T_{w,o}$	T_{air}	Drop in water temp.
1.	.4	312.0	305.4	295	6.6
2.	.6	312.0	304.2	295	7.8
3.	.8	312.0	303.3	295	8.7
4.	1.0	312.0	302.6	295	9.4
5.	1.4	312.0	302	295	10.0

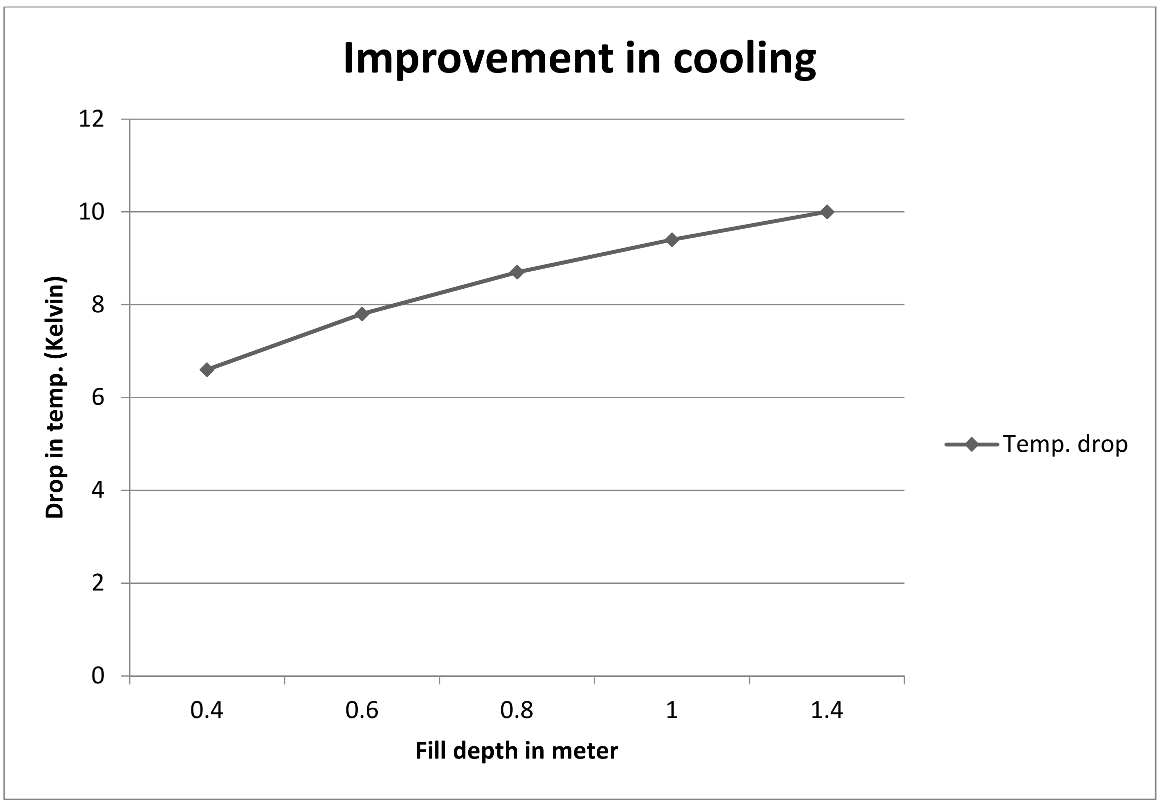

Fig-5.6 Improvement in cooling

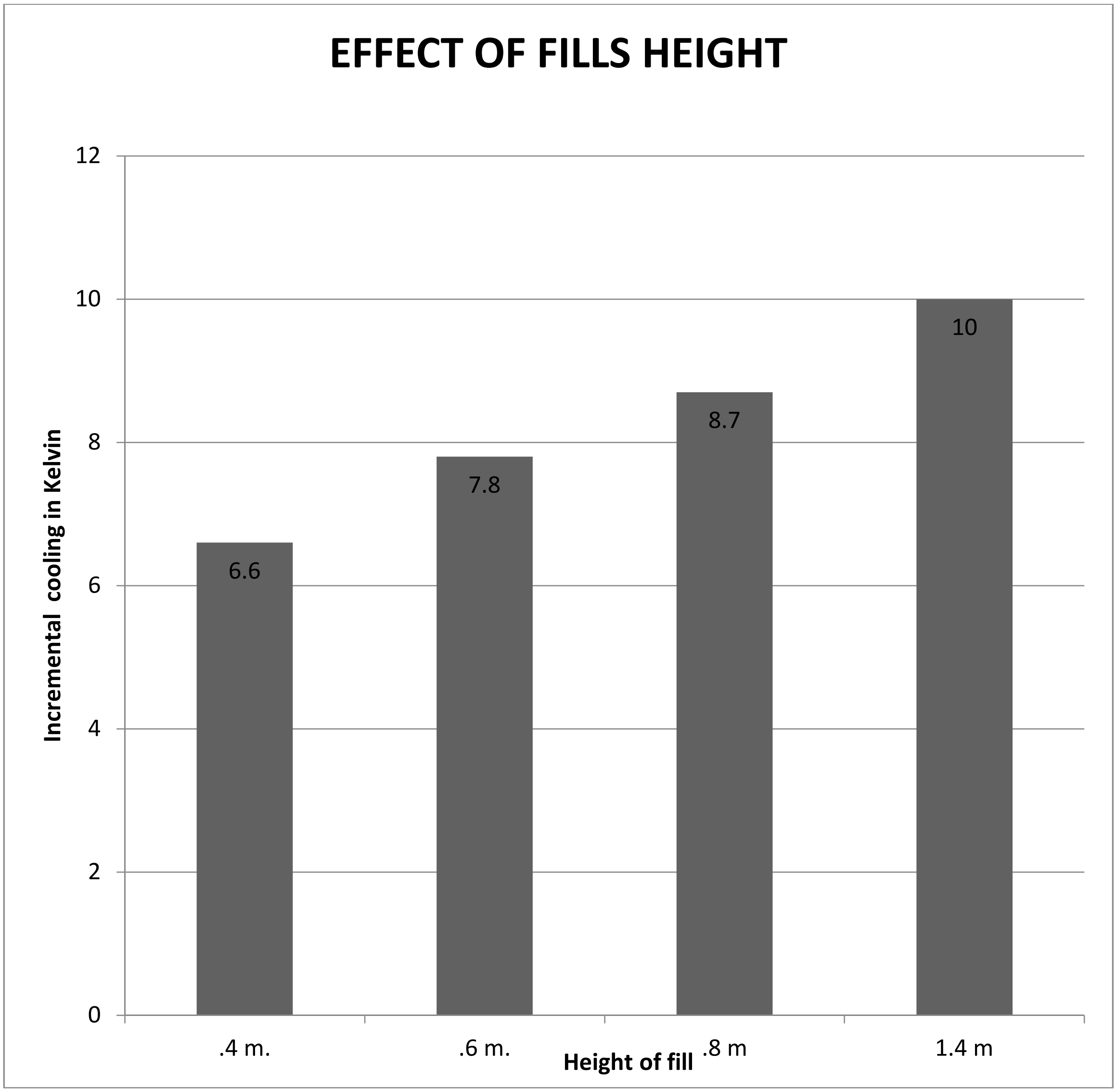

Fig 5.7: Incremental cooling

It has been observed that the cooling rate in the fill increases as the depth of the fill increases. The fill zone shows a good improvement. But this rate of improvement in cooling decreases for the higher fill depth. Fills are the vital zones of cooling so this factor should be taken into consideration.

5.2 EFFECT OF RAIN ZONE HEIGHT ON TOWER PERFORMANCE-

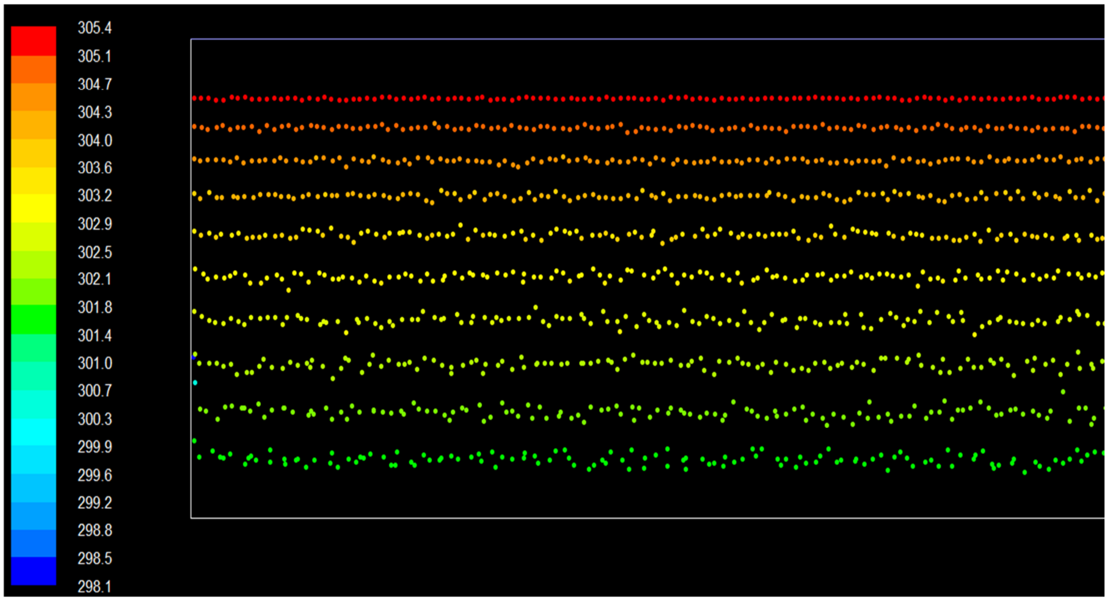

Fig: 5.8a Water temperature variation contour for 7.727 meter height of rain zone

Fig: 5.8a shows the temperature variation in the rain zone of the cooling tower having a height of 7.727 meter. In this picture the water temperature is decreasing up to 301.53 K.

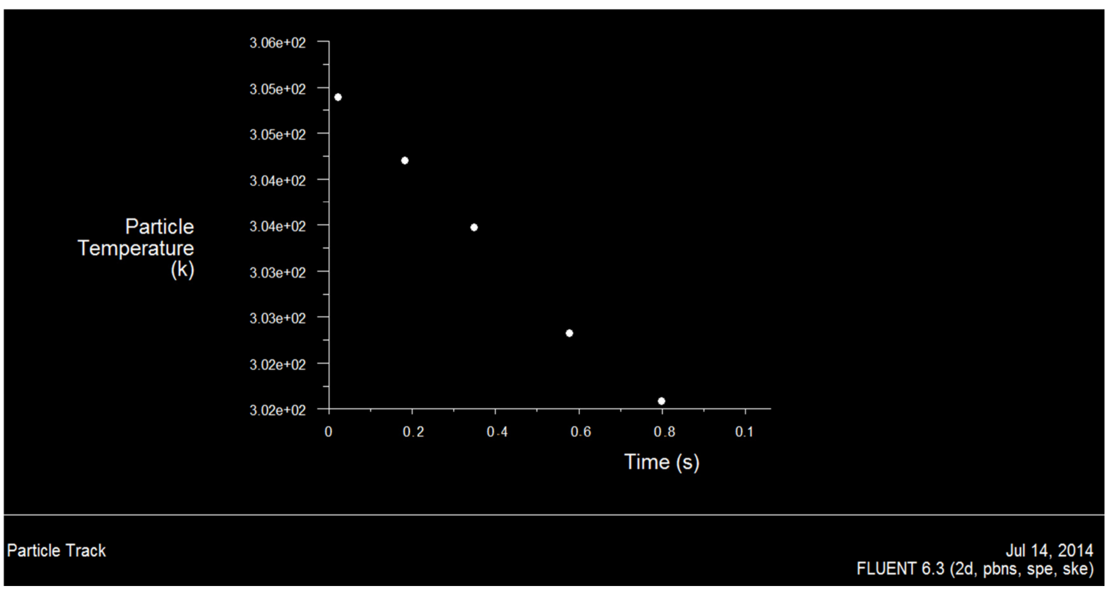

Fig: 5.8b Water temperature variation plot for 7.727 meter height of rain zone

Fig: 5.8b represents temperature vs. time variation. It shows the temperature of water is decreasing up to 301.53 K.

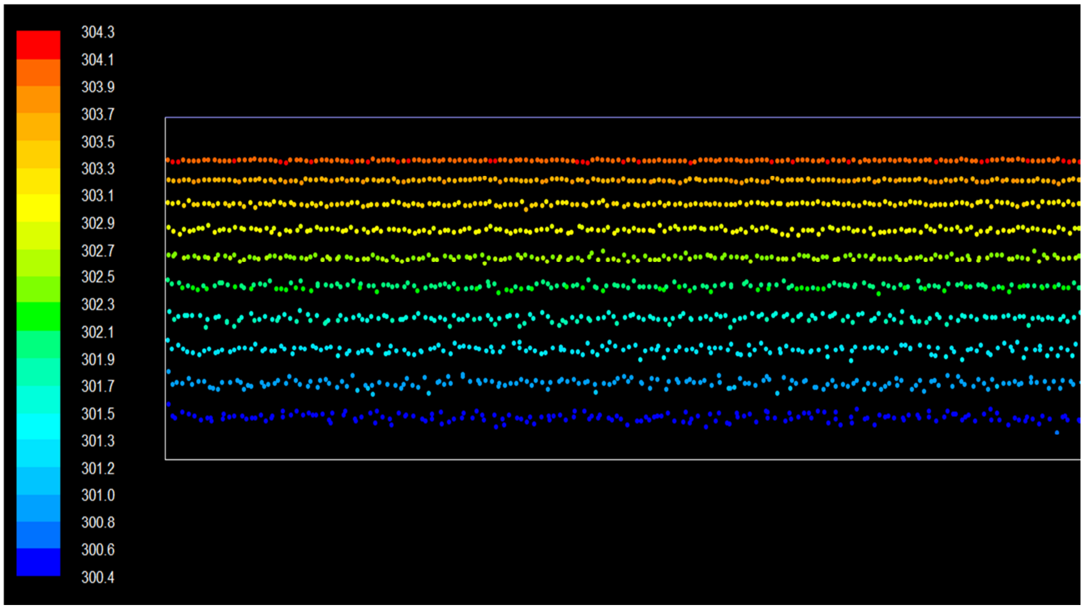

Fig: 5.9a Water temperature variation contour for 7.527 meter height of rain zone

Fig: 5.9a shows the temperature variation in the rain zone of the cooling tower having a height of 7.527 meter. In this picture the water temperature is decreasing up to 300.5 K.

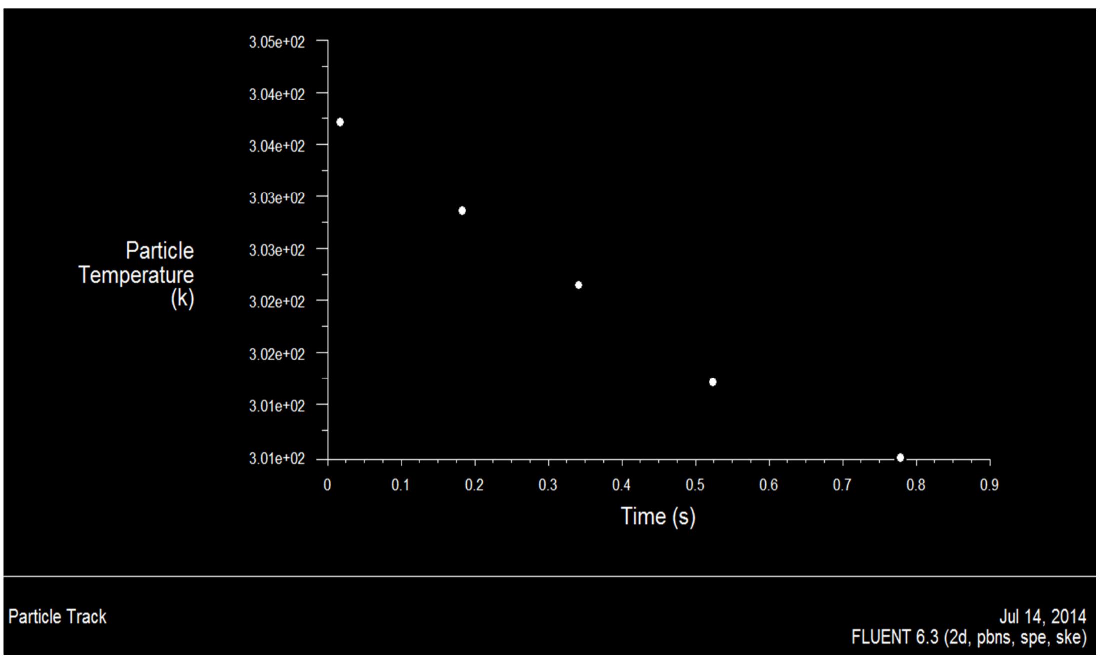

Fig: 5.9b Water temperature variation plot for 7.527 meter height of rain zone

Fig: 5.9b represents temperature vs. time variation. It shows the temperature of water is decreasing up to 300.5 K.

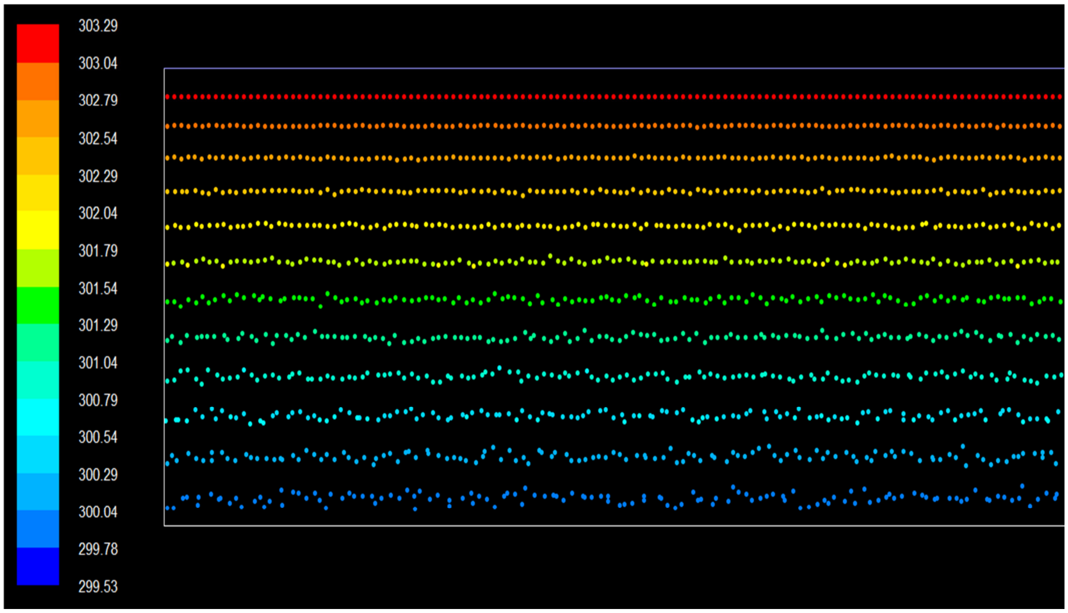

Fig: 5.10a Water temperature variation contour for 7.327 meter height of rain zone

Fig: 5.10a shows the temperature variation in the rain zone of the cooling tower having a height of 7.327 meter. In this picture the water temperature is decreasing up to 299.7 K.

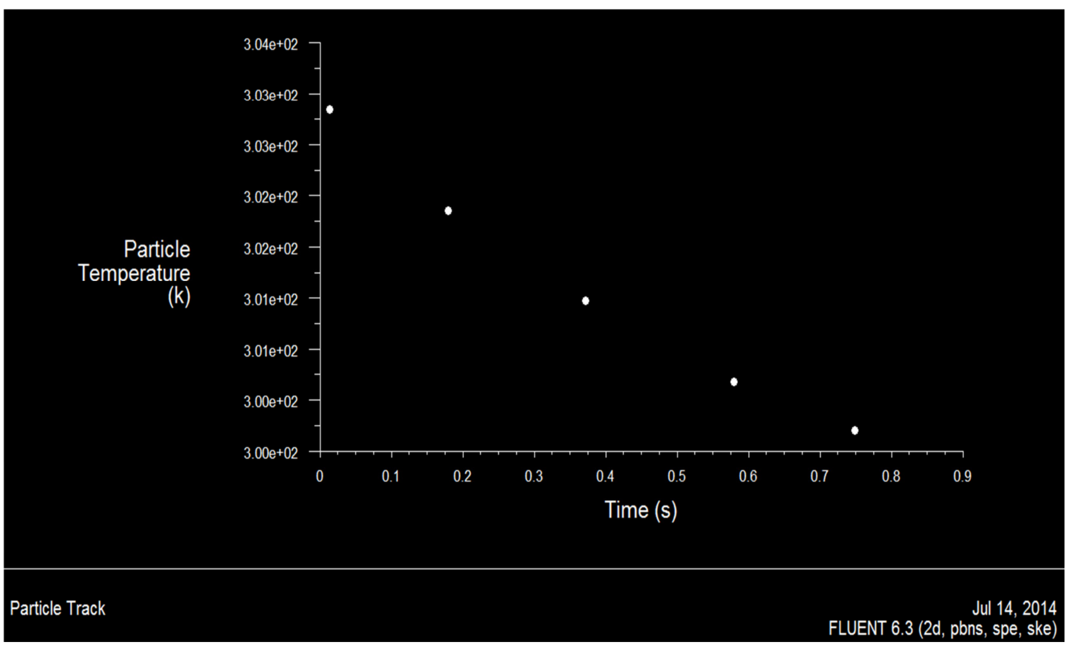

Fig: 5.10b Water temperature variation plot for 7.327 meter height of rain zone

Fig: 5.10b represents temperature vs. time variation. It shows the temperature of water is decreasing up to 299.7 K.

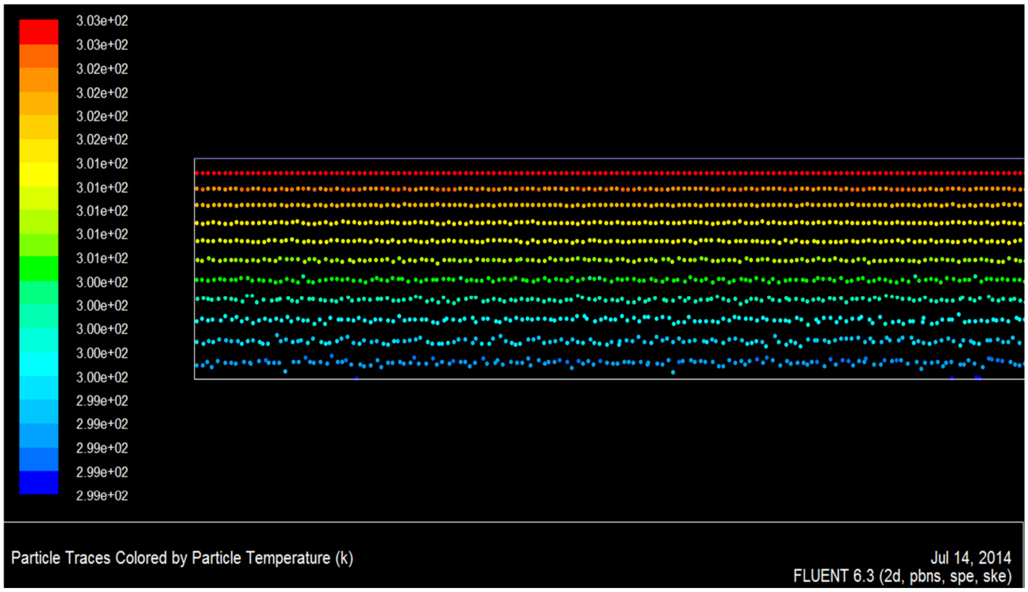

Fig: 5.11a Water Temperature variation contour for 7.127 meter height of rain zone

Fig: 5.11a shows the temperature variation in the rain zone of the cooling tower having a height of 7.127 meter. In this picture the water temperature is decreasing up to 299.1 K.

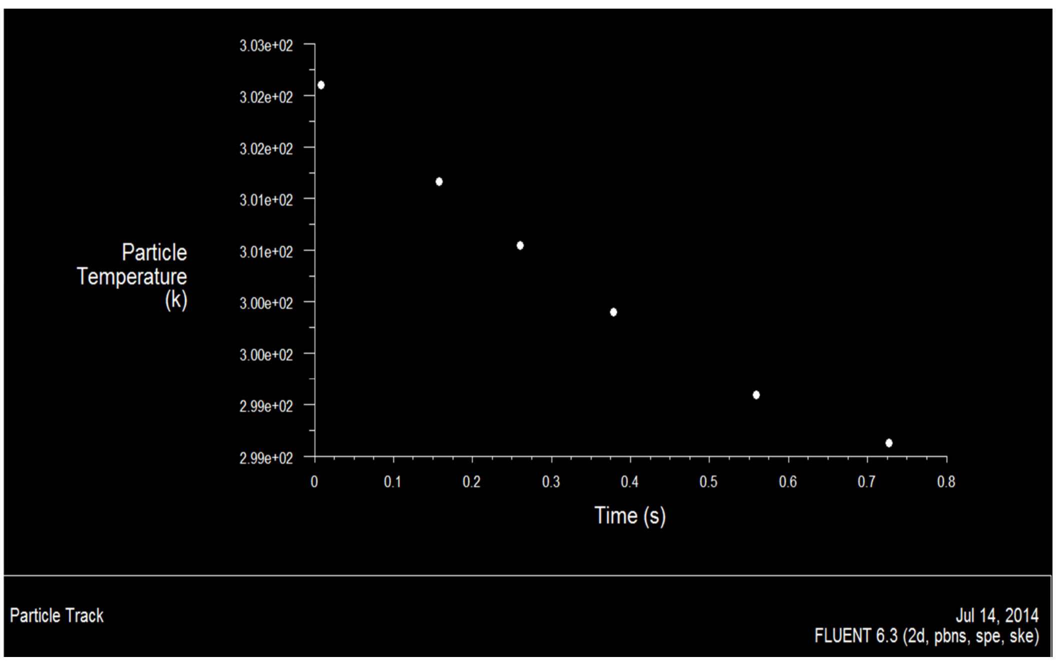

Fig: 5.11b Water Temperature variation plot for 7.127 meter height of rain zone

Fig: 5.11b represents temperature vs. time variation. It shows the temperature of water is decreasing up to 299.1 K.

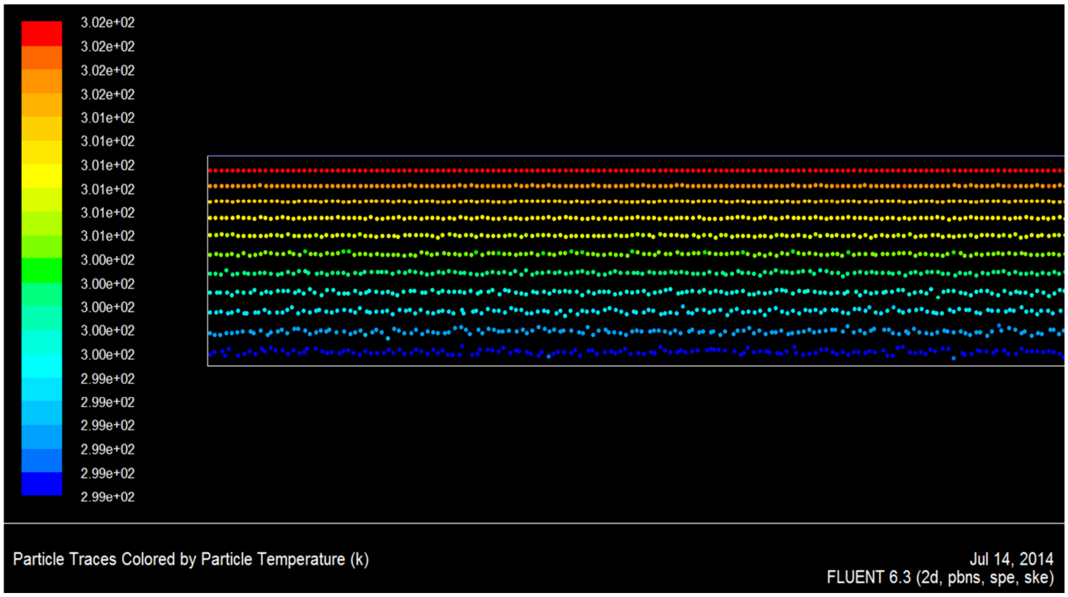

Fig: 5.12a Water Temperature variation contour for 6.727 meter height of rain zone

Fig: 5.12a shows the temperature variation in the rain zone of the cooling tower having a height of 6.727 meter. In this picture the water temperature is decreasing up to 298.8 K.

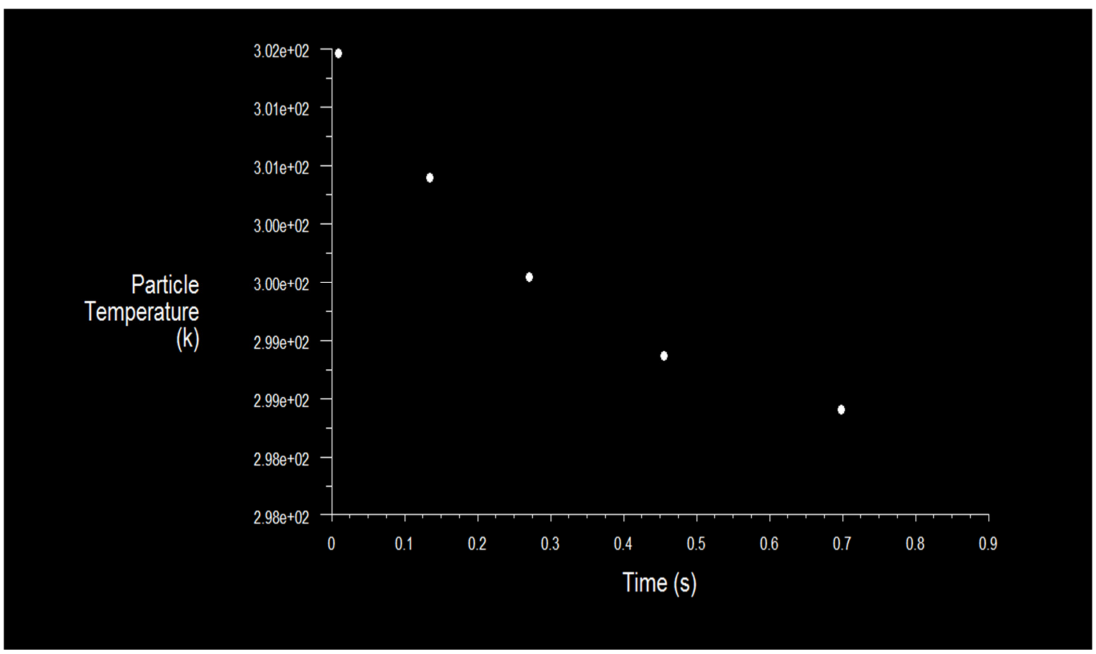

Fig: 5.12b Water Temperature variation plot for 6.727 meter height of rain zone

Fig: 5.12b represents temperature vs. time variation. It shows the temperature of water is decreasing up to 298.8 K.

The effect of rain zone height on the cooling is shown in the table below for the standard reference cooling tower.

Table-5.2: Effect of rain zone height

Sr. No.	HEIGHT	TEMP OF AIR INLET	WATER INLET TEMP.	WATER OUTLET TEMP.	DROP IN WATER TEMP.
1.	7.727	295.0	305.4	301.53	3.87
2.	7.527	295.0	304.2	300.5	3.7
3.	7.327	295.0	303.3	299.7	3.6
4.	7.127	295.0	302.6	299.18	3.42
5.	6.727	295.0	302.0	298.8	3.2

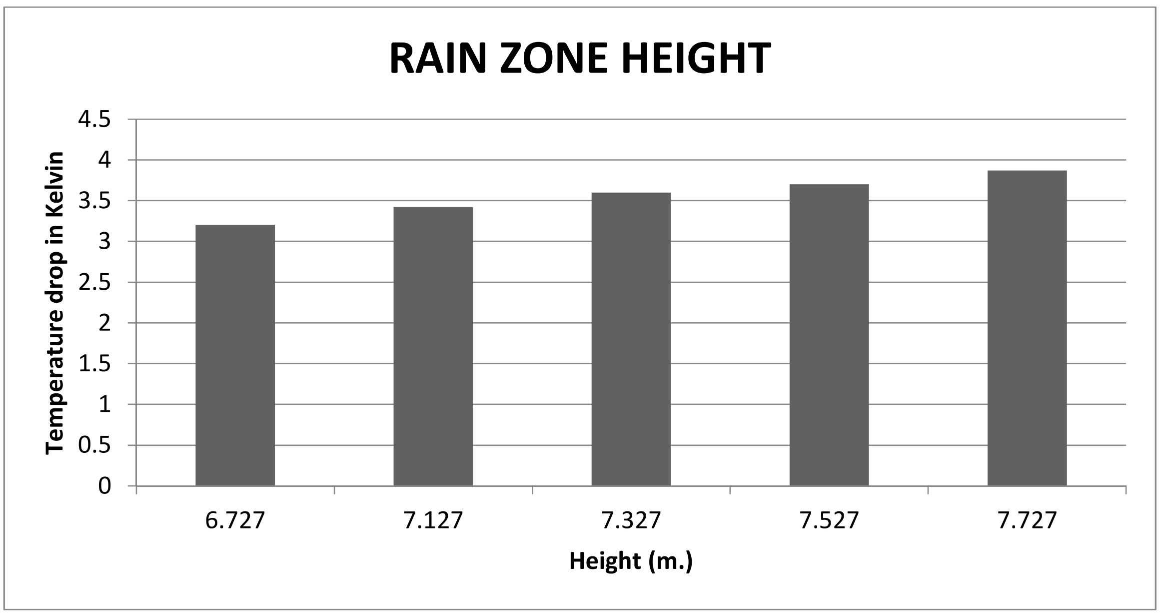

Fig 5.13: Effect of rain zone

The result shows that the degree of cooling decreases as the rain zone height decreases which is primarily due to two reasons the first is that for a lower height the residence time of droplets is low and the second is because of the lower difference in the saturation pressure and the vapor pressure which is the driving force for vaporization.

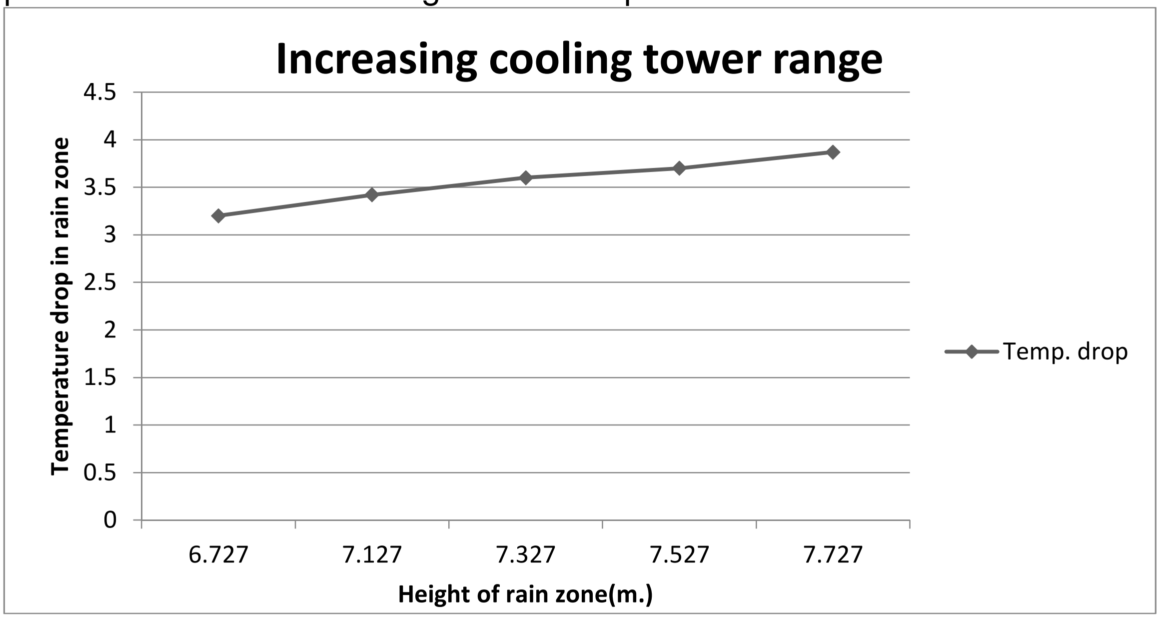

Fig 5.14 Temperature drop in rain zone

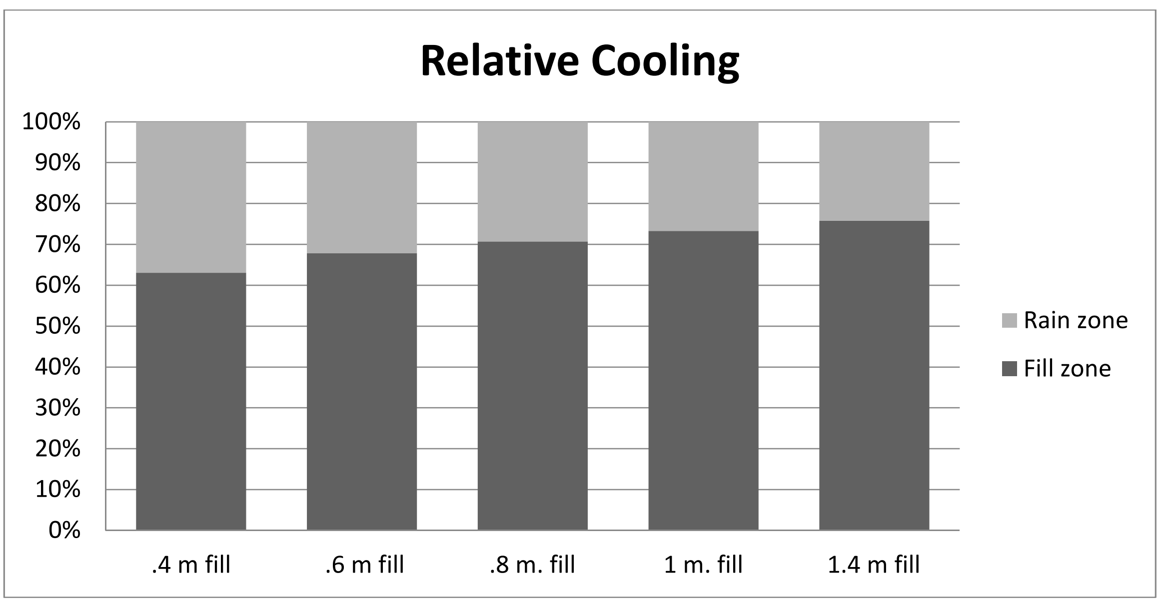

Fig: 5.15 Percentage drop in water temp. for variable heights

5.3 EFFECT OF VARIABLE MASS FLOW RATE ON COOLING IN FILL ZONE-

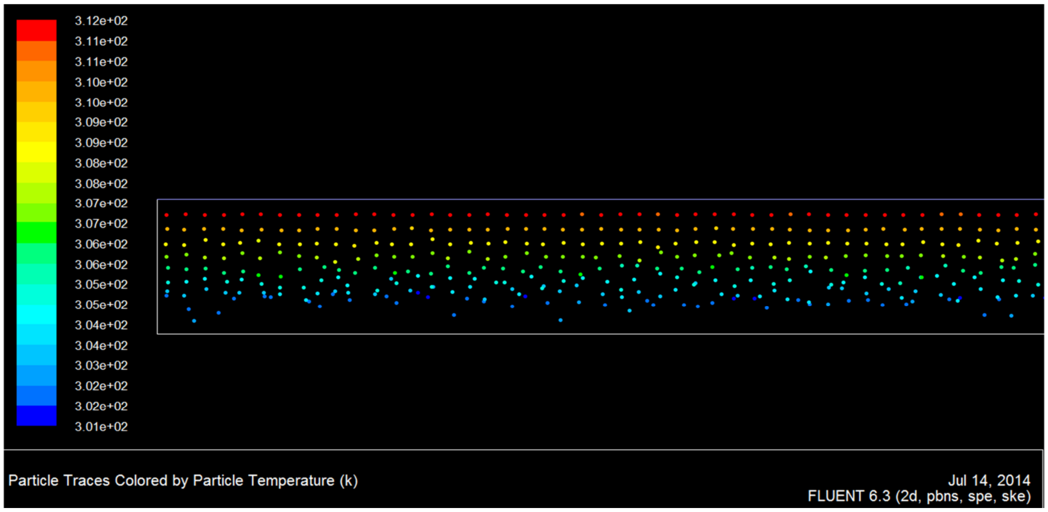

Fig: 5.16a Water temperature variation for fill zone at 12500 kg/s mass flow rate of water

Fig: 5.16a shows the temperature variation in the fill zone of the cooling tower having a height of 1 meter. In this picture the water temperature is decreasing up to 301.5 K.

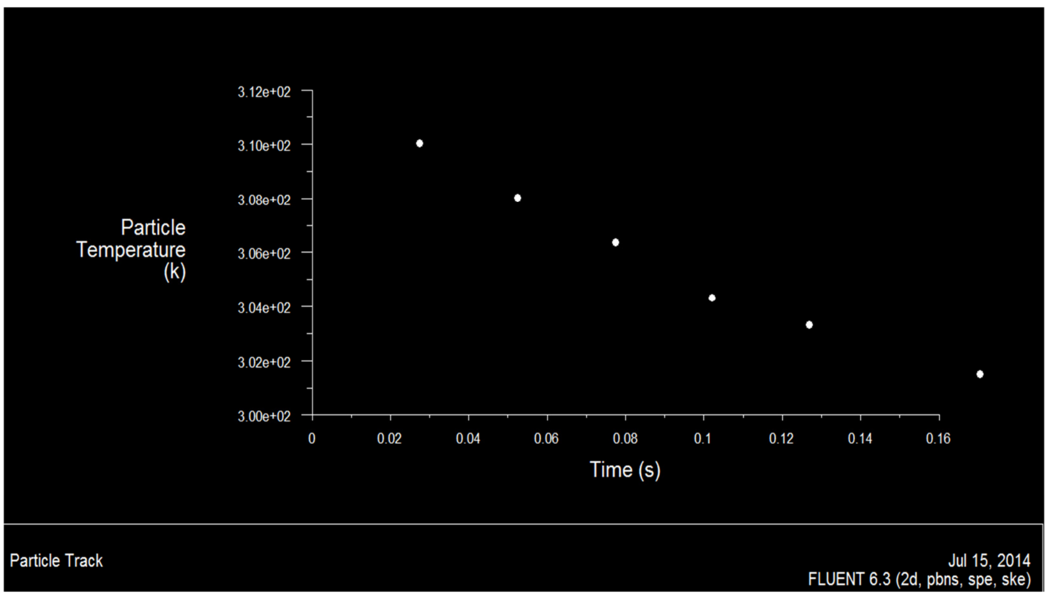

Fig: 5.16b Water temperature variation plot for fill zone at 12500 kg/s mass flow rate of water

Fig: 5.16b represents temperature vs. time variation. It shows the temperature of water is decreasing up to 301.5 K

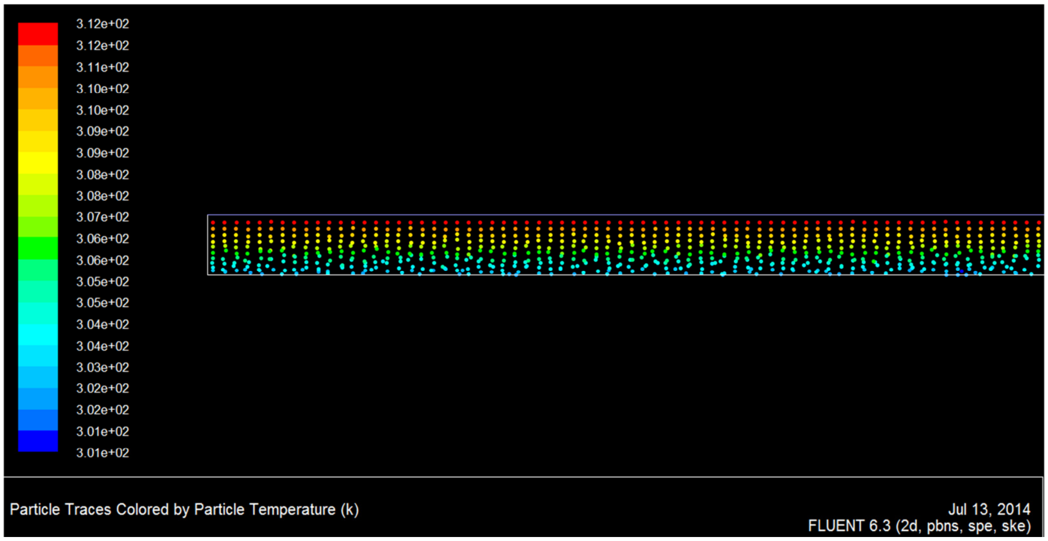

Fig: 5.17a Water temperature variation for fill zone at 15000 kg/s mass flow rate of water

Fig: 5.17a shows the temperature variation in the fill zone of the cooling tower having a height of 1 meter. In this picture the water temperature is decreasing up to 302.4 K.

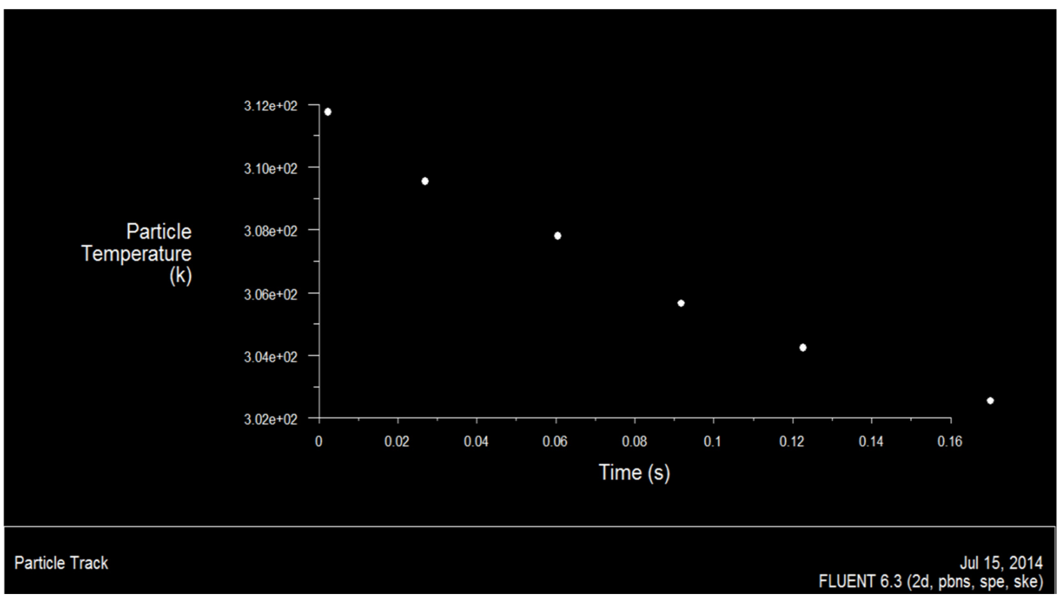

Fig: 5.17b Water temperature variation plot for fill zone at 15000 kg/s mass flow rate of water

Fig: 5.17b represents temperature vs. time variation. It shows the temperature of water is decreasing up to 302.4 K

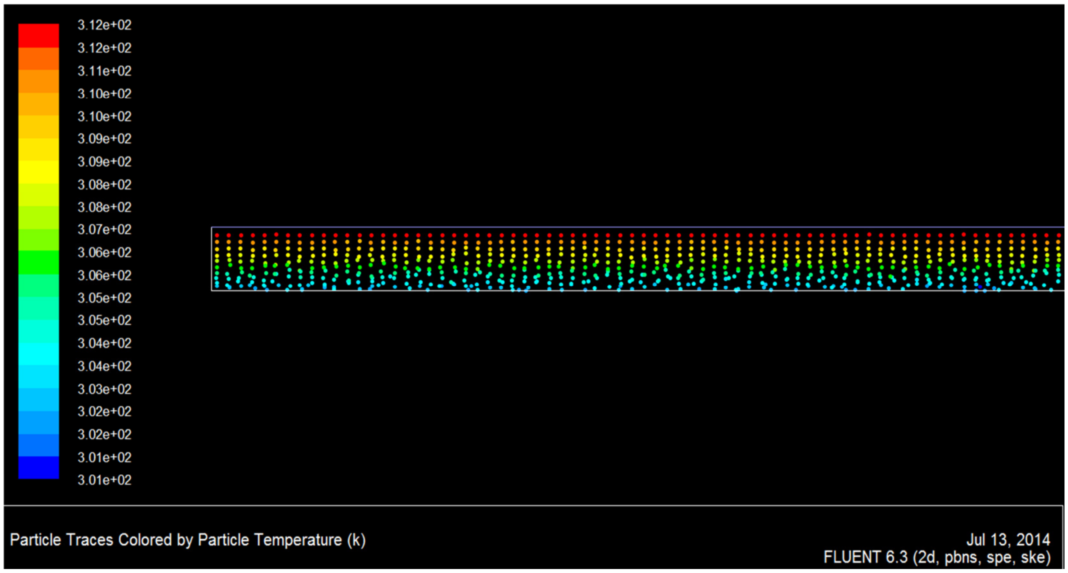

Fig: 5.18a Water temperature variation for fill zone at 13750 kg/s mass flow rate of water

Fig: 5.18a shows the temperature variation in the fill zone of the cooling tower having a height of 1 meter. In this picture the water temperature is decreasing up to 301.9 K.

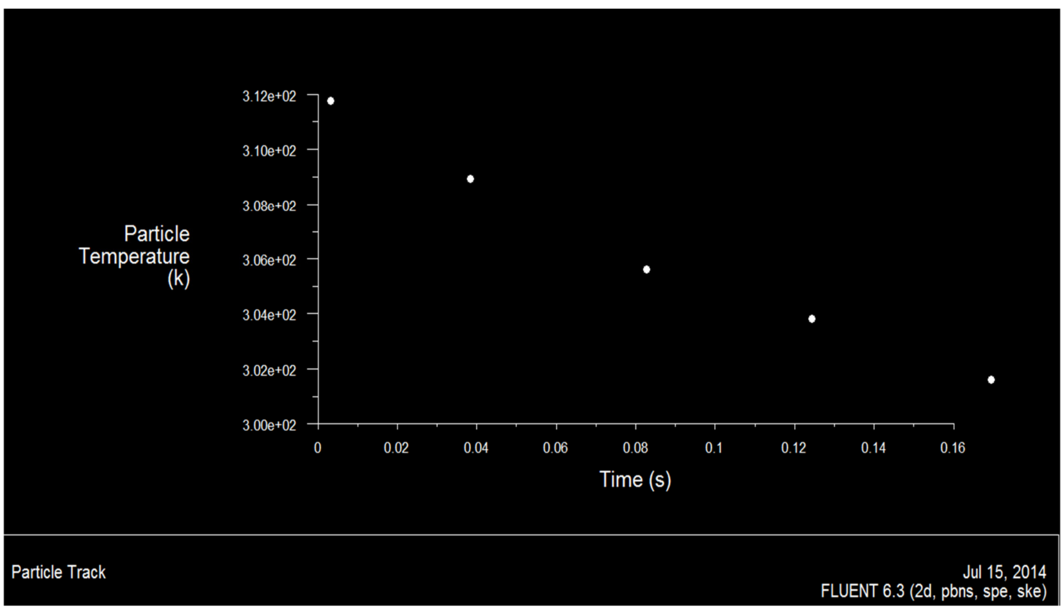

Fig: 5.18b Water temperature variation plot for fill zone at 13750 kg/s mass flow rate of water

Fig: 5.18b represents temperature vs. time variation. It shows the temperature of water is decreasing up to 301.9 K.

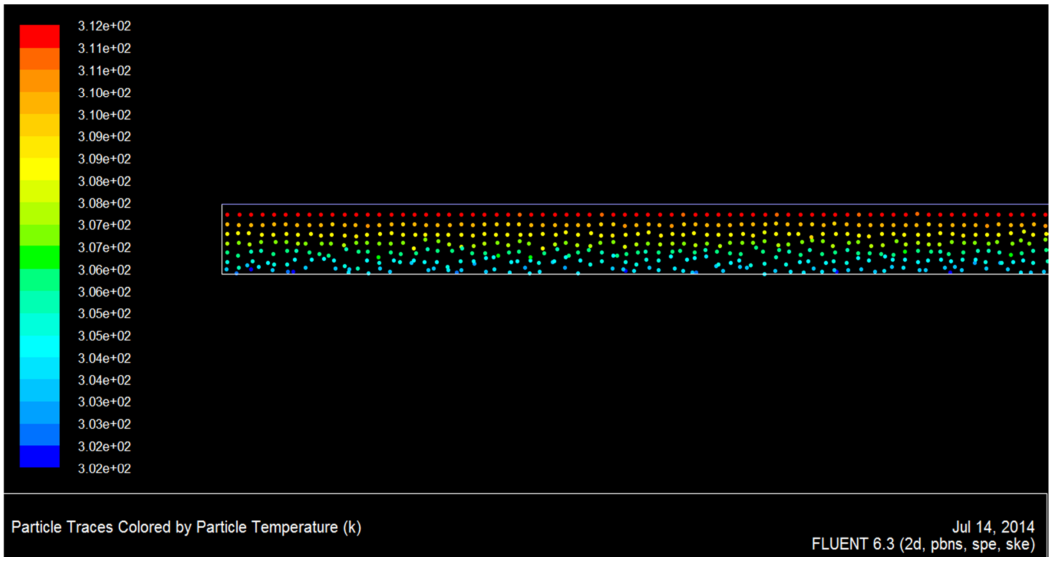

Fig: 5.19a Water temperature variation for fill zone at 18000 kg/s mass flow rate of water

Fig: 5.19a shows the temperature variation in the fill zone of the cooling tower having a height of 1 meter. In this picture the water temperature is decreasing up to 303.8 K.

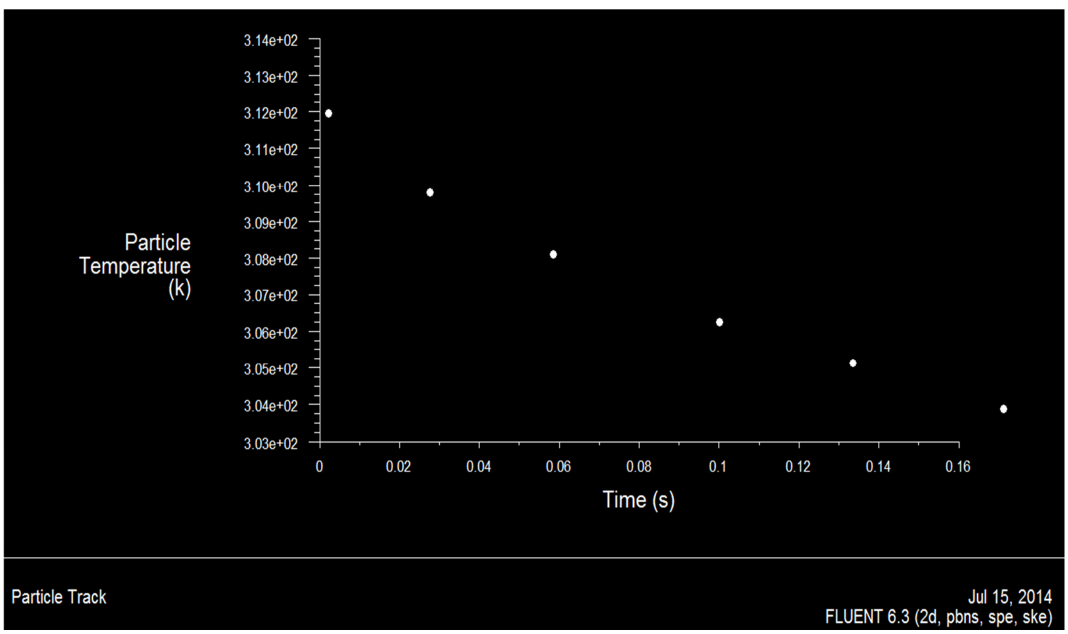

Fig: 5.19b Water temperature variation plot for fill zone at 18000 kg/s mass flow rate of water

Fig: 5.19b represents temperature vs. time variation. It shows the temperature of water is decreasing up to 303.8 K.

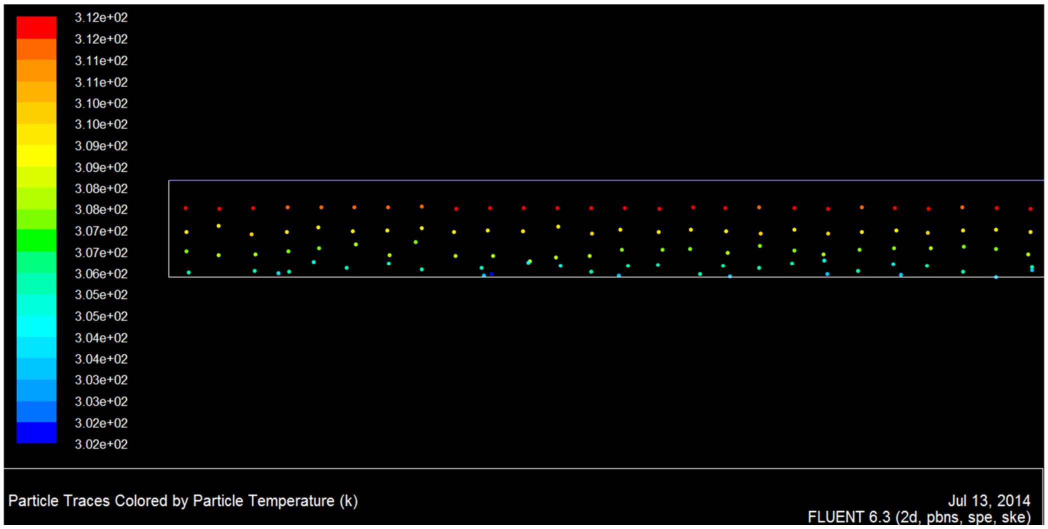

Fig: 5.20a Water temperature variation for fill zone at 29000 kg/s mass flow rate of water

Fig: 5.20a shows the temperature variation in the fill zone of the cooling tower having a height of 1 meter. In this picture the water temperature is decreasing up to 306.25 K.

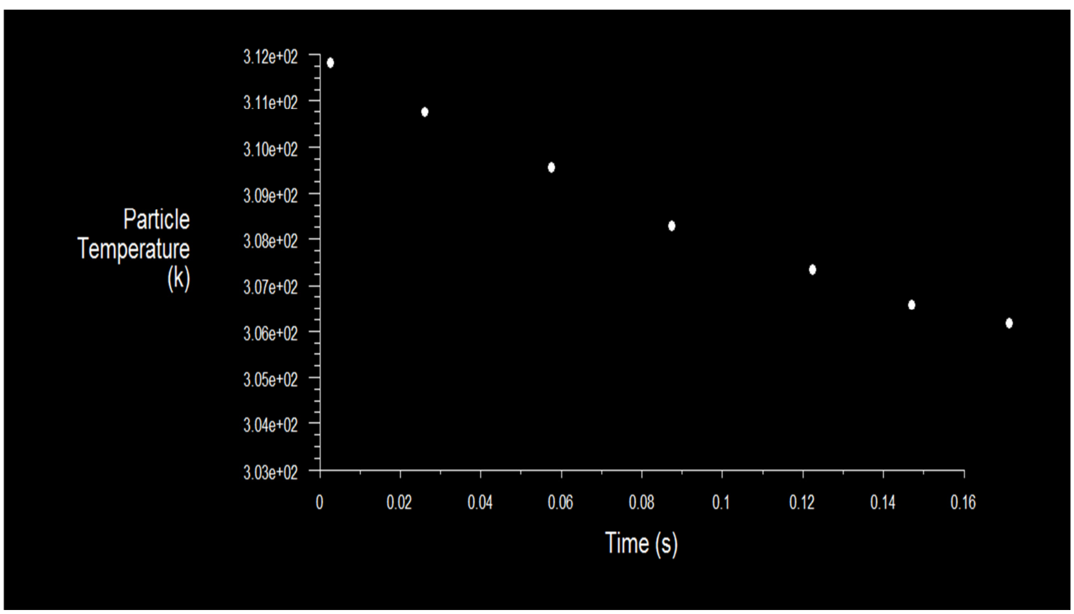

Fig: 5.20b Water temperature variation plot for fill zone at 29000 kg/s mass flow rate of water

Fig: 5.20b represents temperature vs. time variation. It shows the temperature of water is decreasing up to 306.25 K.

The drop in water temperature in the fill zone decreases as the mass flow rate of the water is increased this less air available per unit mass of water and so the less diffusion and low heat transfer is accountable for this phenomenon. The sufficient/good evaporation in this condition is not possible because air will now get more humid early.

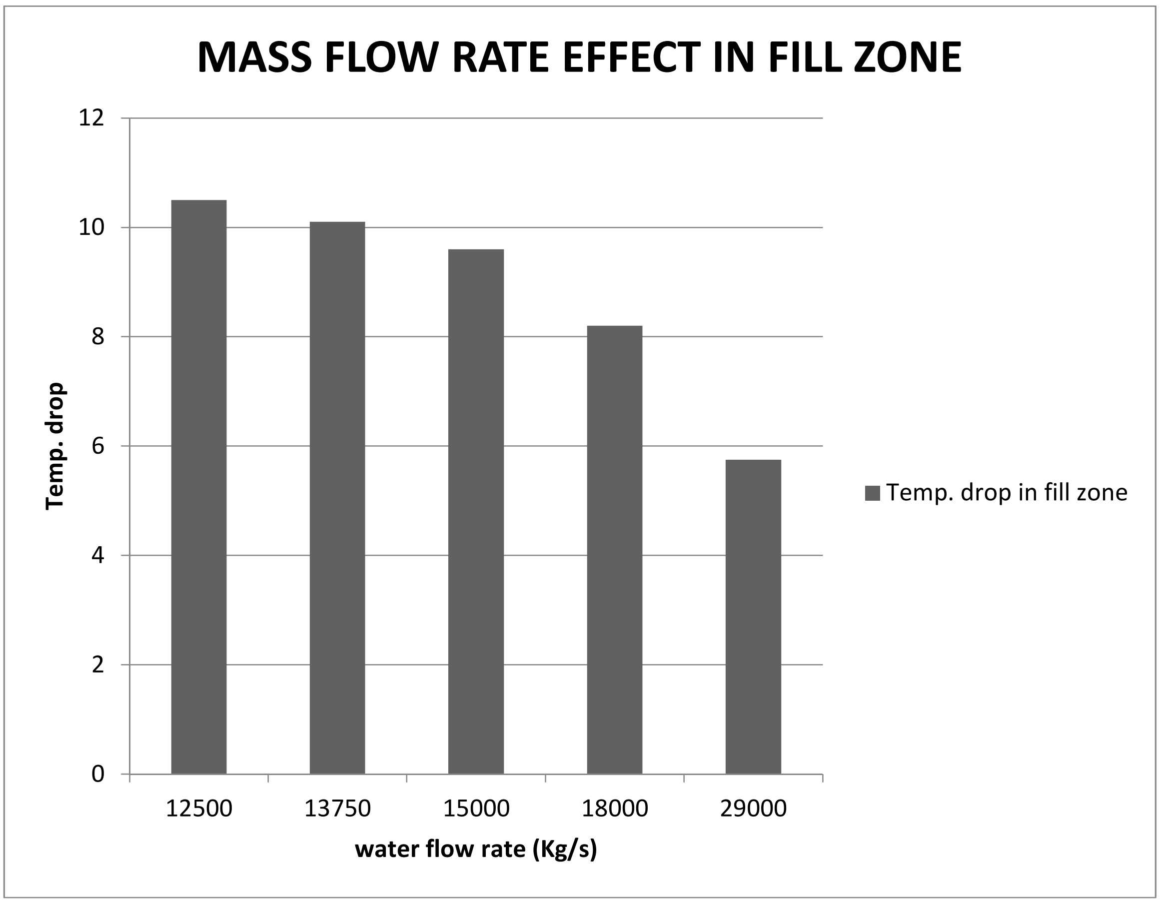

Fig 5.21 Cooling in fill zone for different flow rates

5.4 EFFECT OF VARIABLE MASS FLOW RATE ON COOLING IN RAIN ZONE

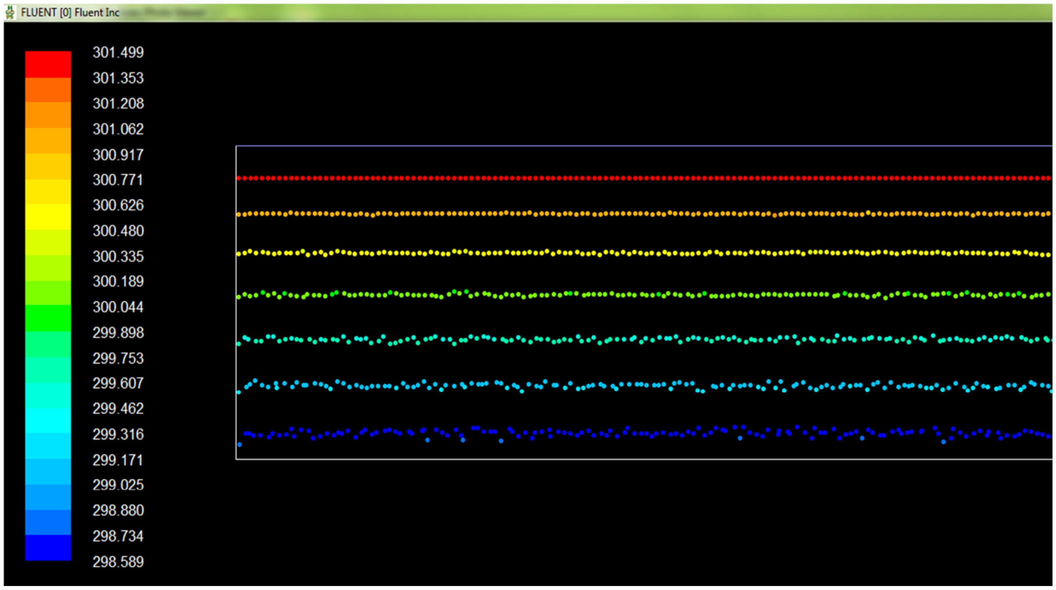

Fig: 5.22a Water temperature variation for rain zone at 12500 kg/s mass flow rate of water

Fig: 5.22a shows the temperature variation in the rain zone of the cooling tower having a height of 7.127 meter. In this picture the water temperature is decreasing up to 298.58 K

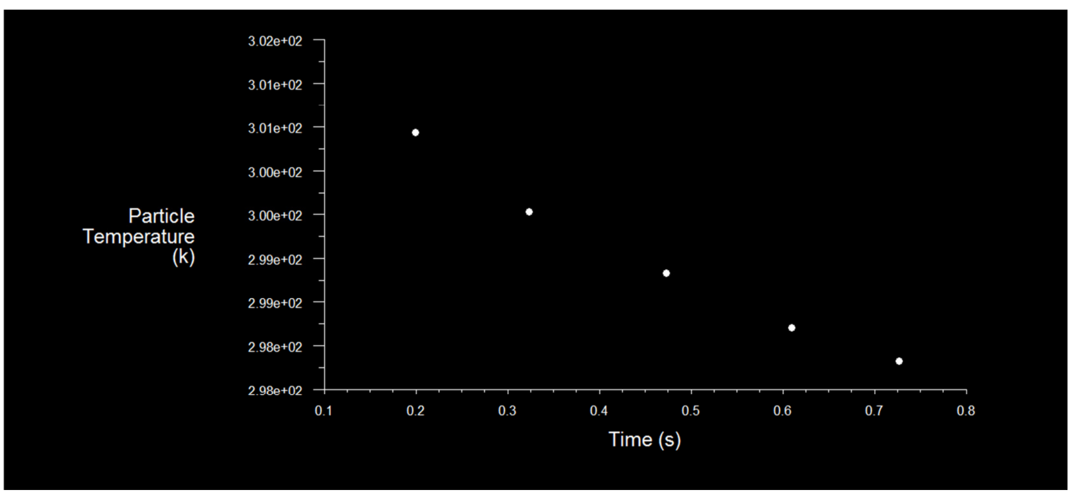

Fig: 5.22b Water temperature variation plot for rain zone at 12500 kg/s mass flow rate of water

Fig: 5.22b represents temperature vs. time variation. It shows the temperature of water is decreasing up to 298.58 K.

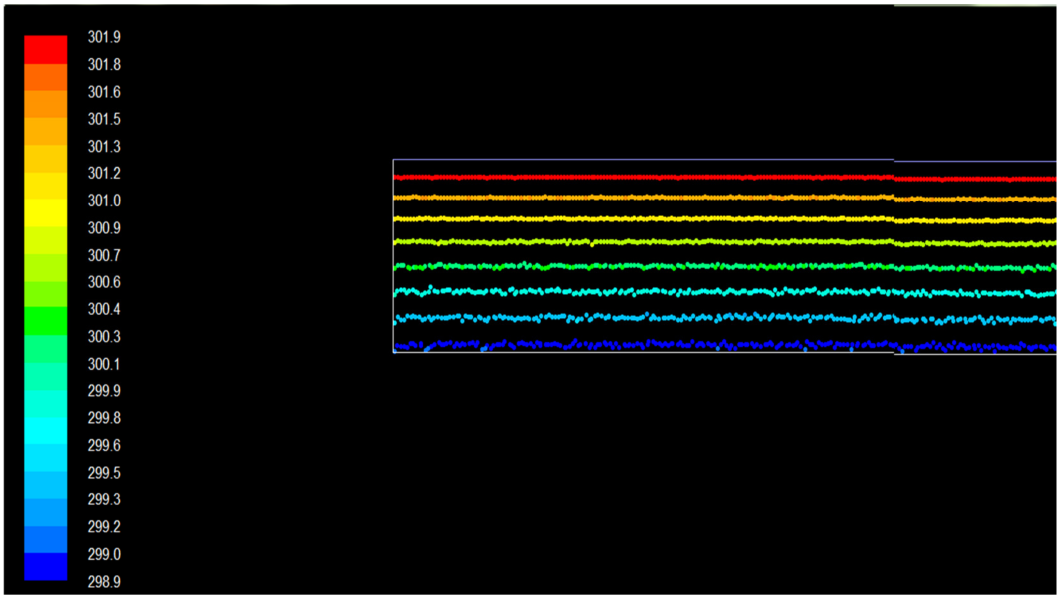

Fig: 5.23a Water temperature variation for rain zone at 13750 kg/s mass flow rate of water

Fig: 5.23a shows the temperature variation in the rain zone of the cooling tower having a height of 7.127 meter. In this picture the water temperature is decreasing up to 298.9 K

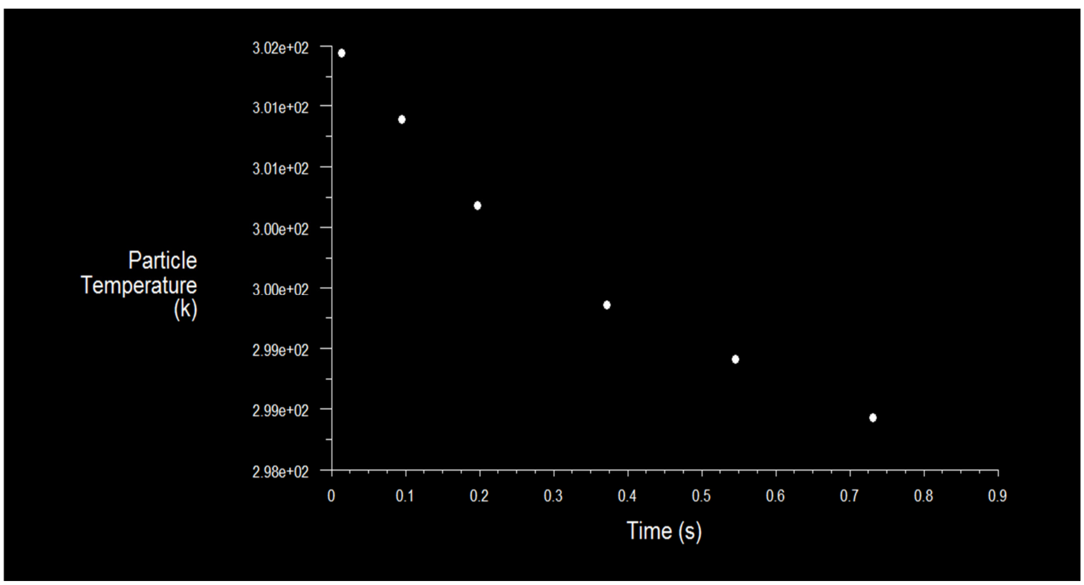

Fig: 5.23b Water temperature variation plot for rain zone at 13750 kg/s mass flow rate of water

Fig: 5.23b represents temperature vs. time variation. It shows the temperature of water is decreasing up to 298.9 K

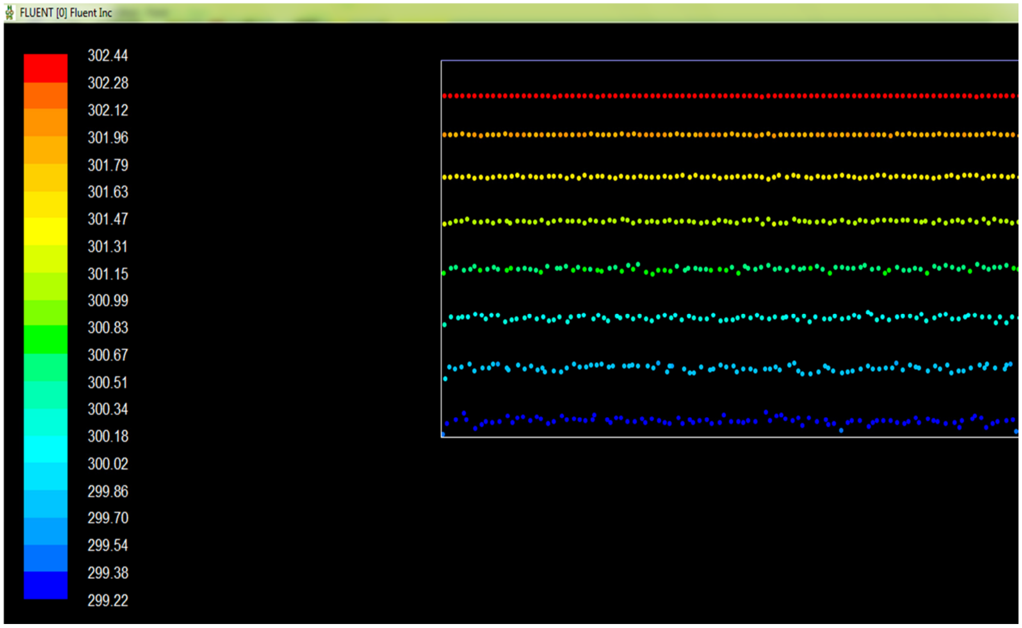

Fig: 5.24a Water temperature variation for rain zone at 13750 kg/s mass flow rate of water

Fig: 5.24a shows the temperature variation contour in the rain zone of the cooling tower having a height of 7.127 meter. In this picture the water temperature is decreasing up to 299.3 K

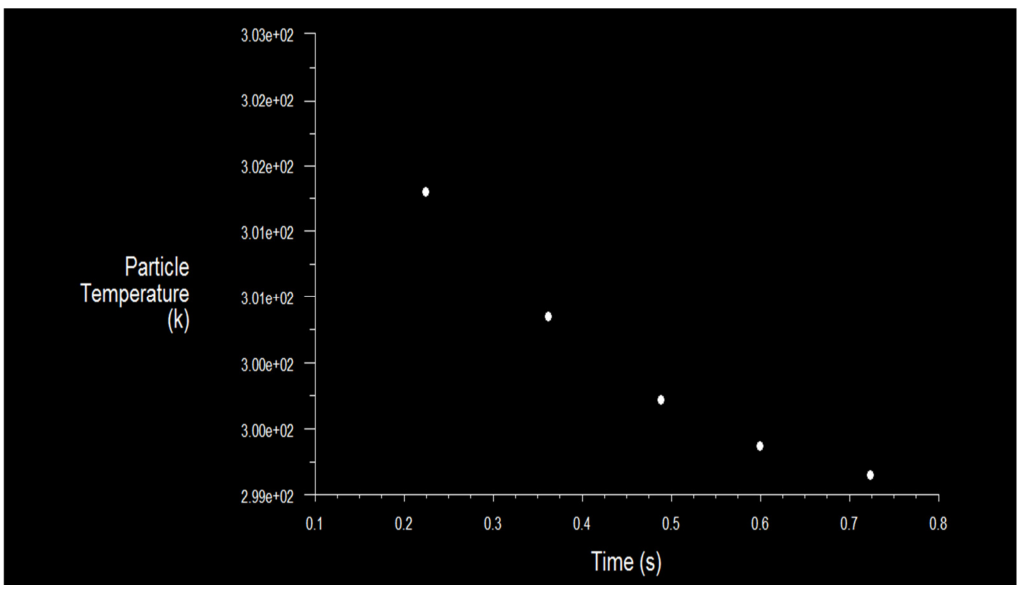

Fig: 5.24b Water temperature variation plot for rain zone at 13750 kg/s mass flow rate of water

Fig: 5.24b represents temperature vs. time variation. It shows the temperature of water is decreasing up to 299.3 K

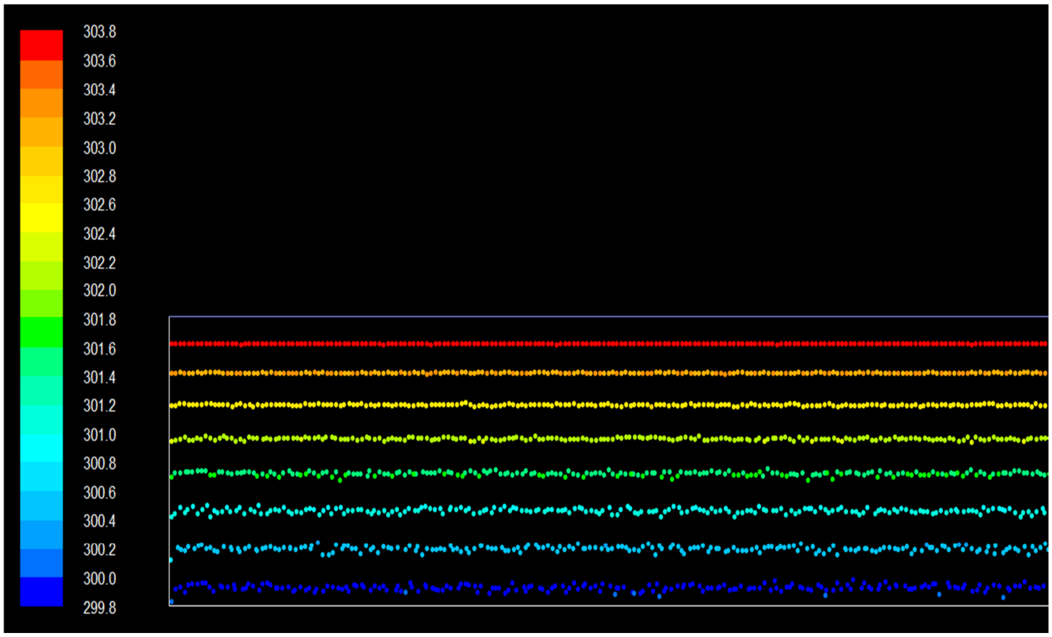

Fig: 5.25a Water temperature variation for rain zone at 35000 kg/s mass flow rate of water

Fig: 5.25a shows the temperature variation in the rain zone of the cooling tower having a height of 7.127 meter. In this picture the water temperature is decreasing up to 299.8 K

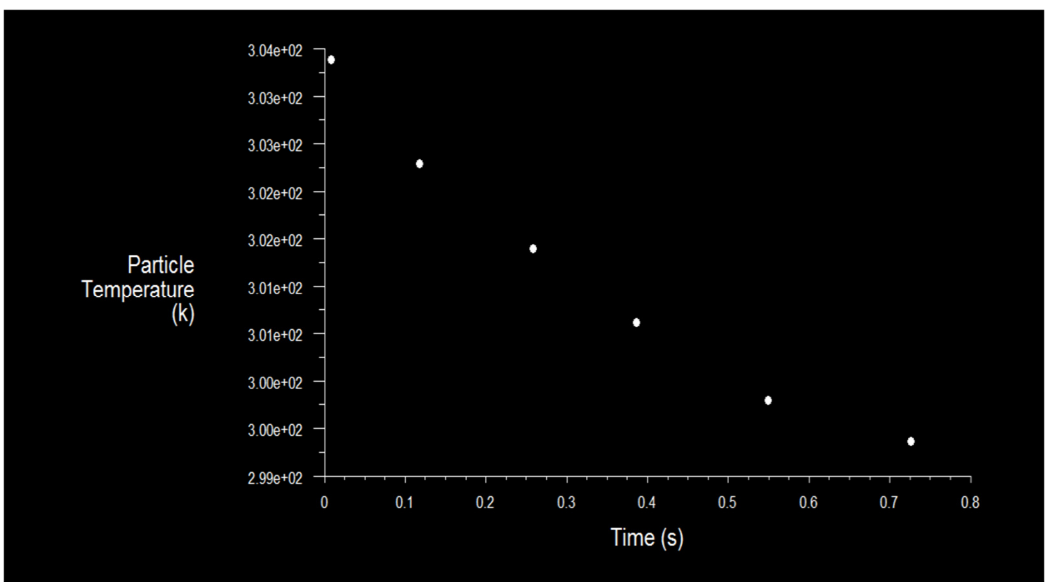

Fig: 5.25b Water temperature variation plot for rain zone at 35000 kg/s mass flow rate of water

Fig: 5.25b represents temperature vs. time variation. It shows the temperature of water is decreasing up to 299.8 K

As the flow rate of water is increased, the less cooling happens in fill zone but now more cooling occurs in the rain zone. The relative contribution of different zones is shown on the diagram. The net higher cooling is observed for less mass flow rate which is shown on the diagram.

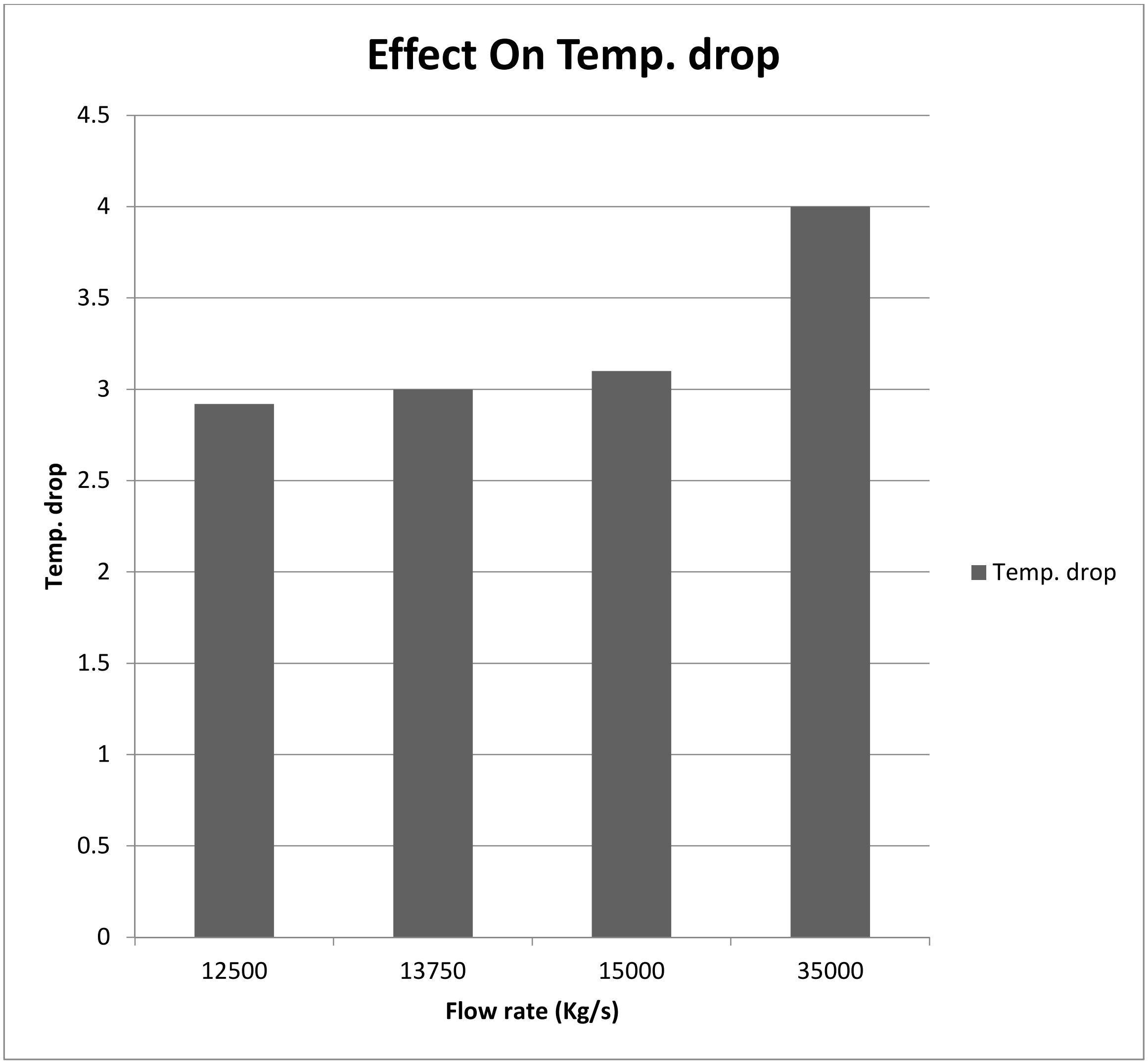

Fig: 5.26-Effect of mass flow rate on rain zone

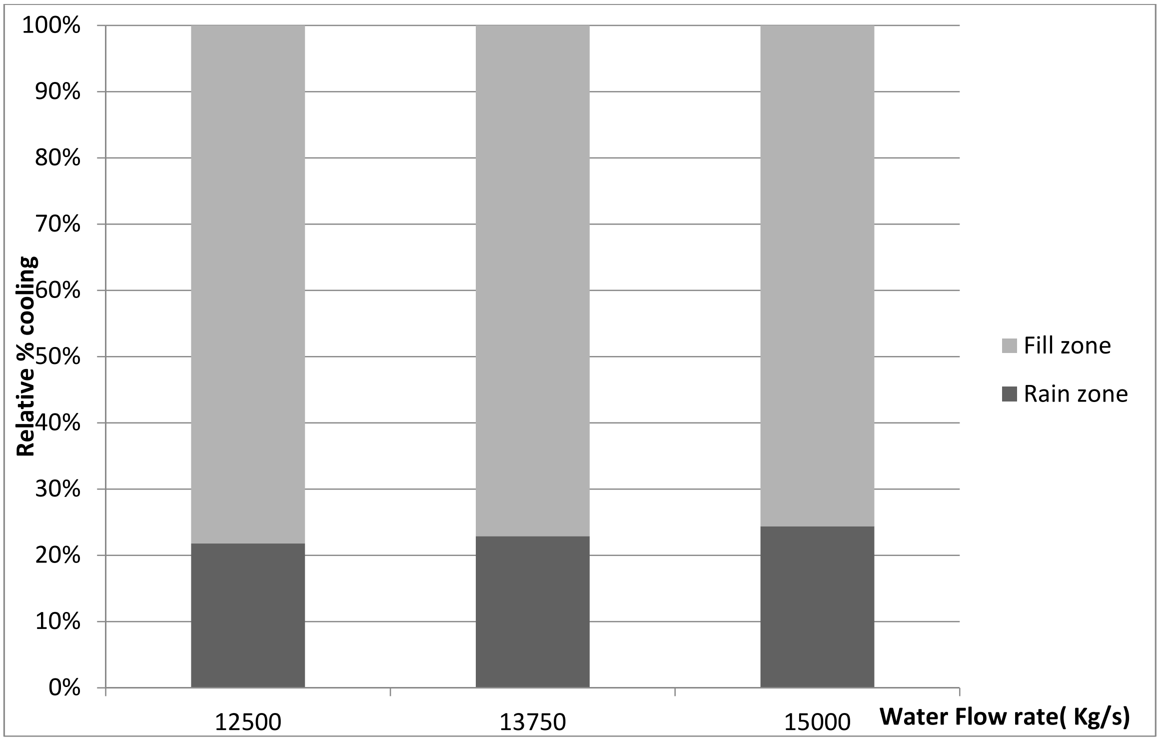

Fig 5.27:-Relative cooling in different zones for different mass flow rates

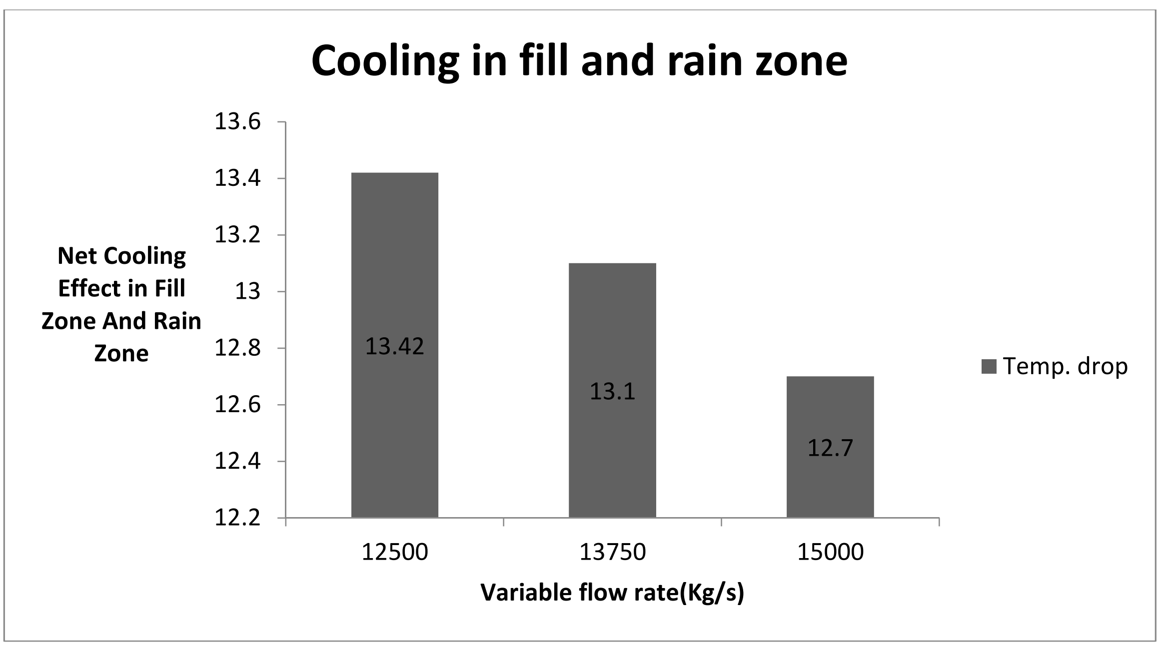

Fig: 5.28-Net cooling for different mass flow rates (for 8.577m inlet height)

5.5 EFFECT OF AIR TEMPERATURE ON COOLING IN FILL ZONE-

In the cases indicated below the temperature drop has been observed for the 290 K, 295 K and 298 K respectively.

CASE 1-

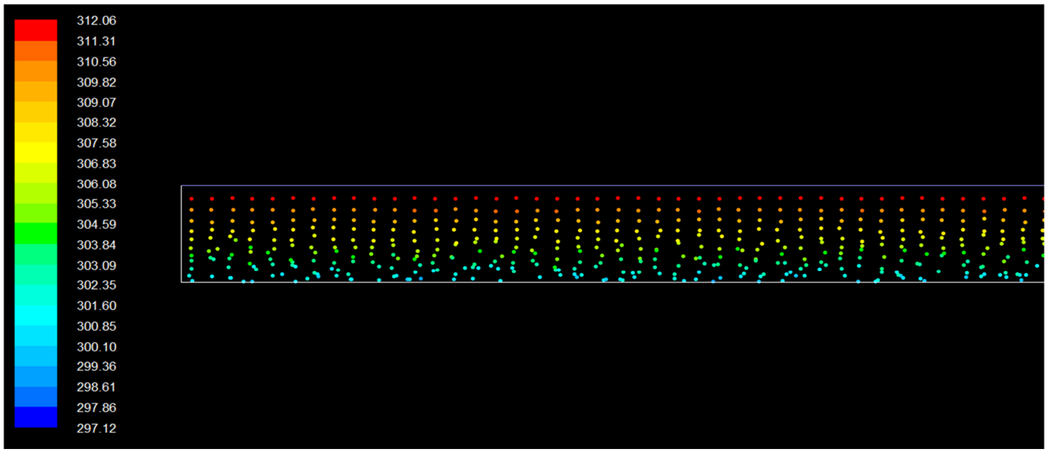

Fig: 5.29a Water temperature variation for fill zone at 290 K inlet air temperature

Fig: 5.29a shows the temperature variation in the fill zone of the cooling tower having a height of 1 meter. In this picture the water temperature is decreasing up to 301.7 K

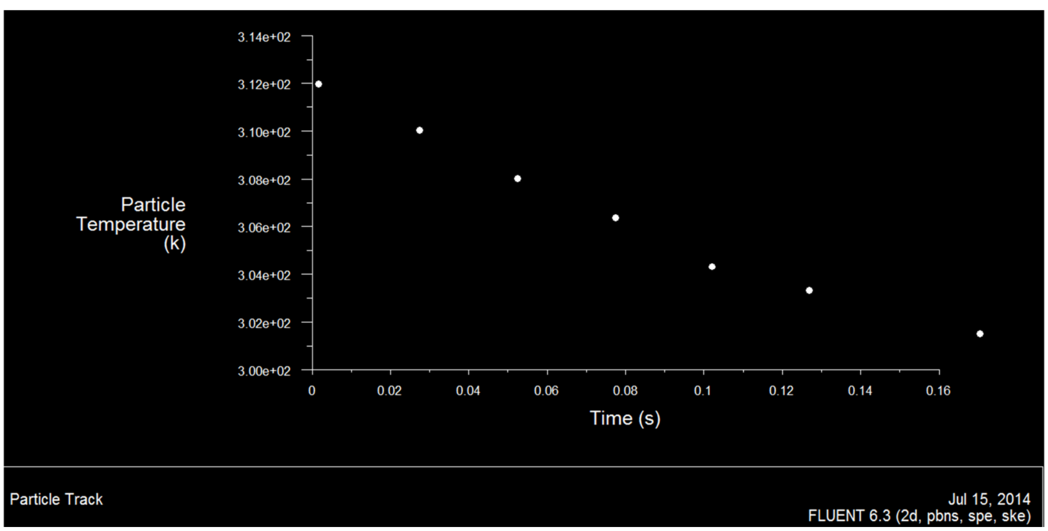

Fig: 5.29b Water temperature variation plot for fill zone at 290 K inlet air temperature

Fig: 5.29b represents temperature vs. time variation. It shows the temperature of water is decreasing up to 301.7 K.

CASE 2-

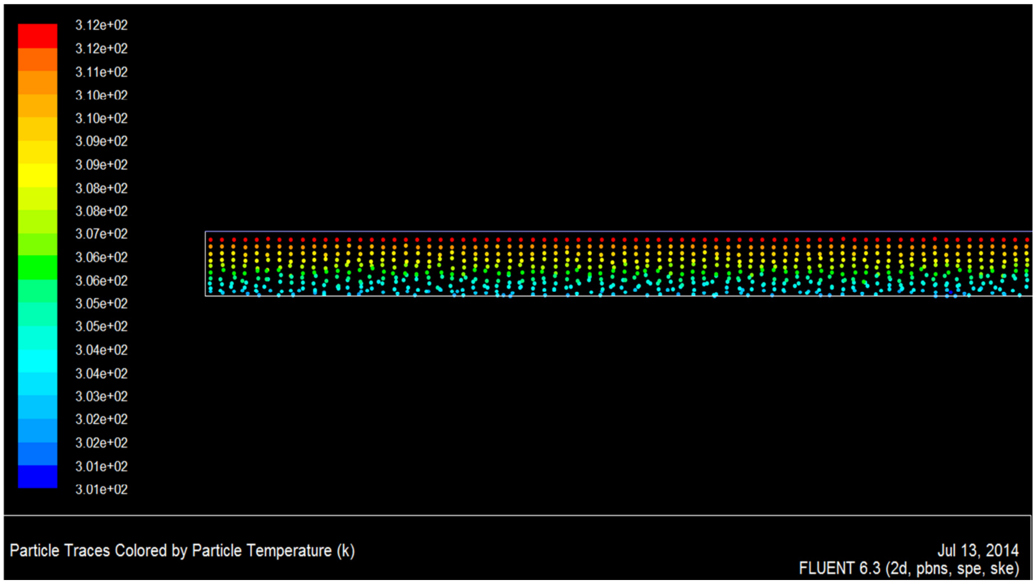

Fig: 5.30a Water temperature variation for fill zone at 295 K air temperature

Fig: 5.30a shows the temperature variation in the fill zone of the cooling tower having a height of 1 meter. In this picture the water temperature is decreasing up to 302.6 K.

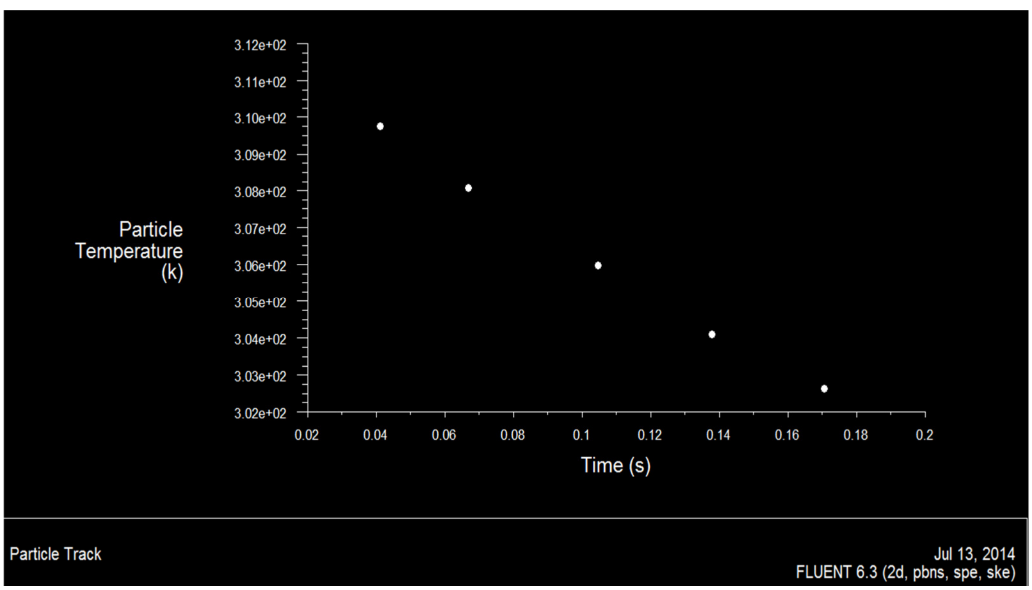

Fig: 5.30b Water temperature variation plot for fill zone at 295 K inlet air temperature

Fig: 5.30b represents temperature vs. time variation. It shows the temperature of water is decreasing up to 302.6 K.

CASE 3-

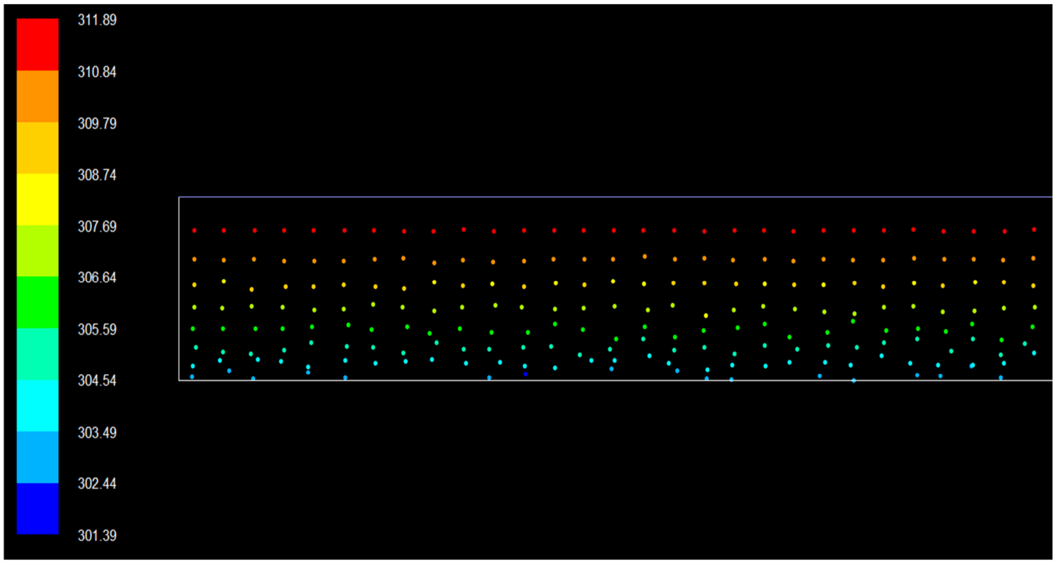

Fig: 5.31a Water temperature variation for fill zone at 298 K inlet air temperature

Fig: 5.31a shows the temperature variation in the fill zone of the cooling tower having a height of 1 meter. In this picture the water temperature is decreasing up to 303.2 K.

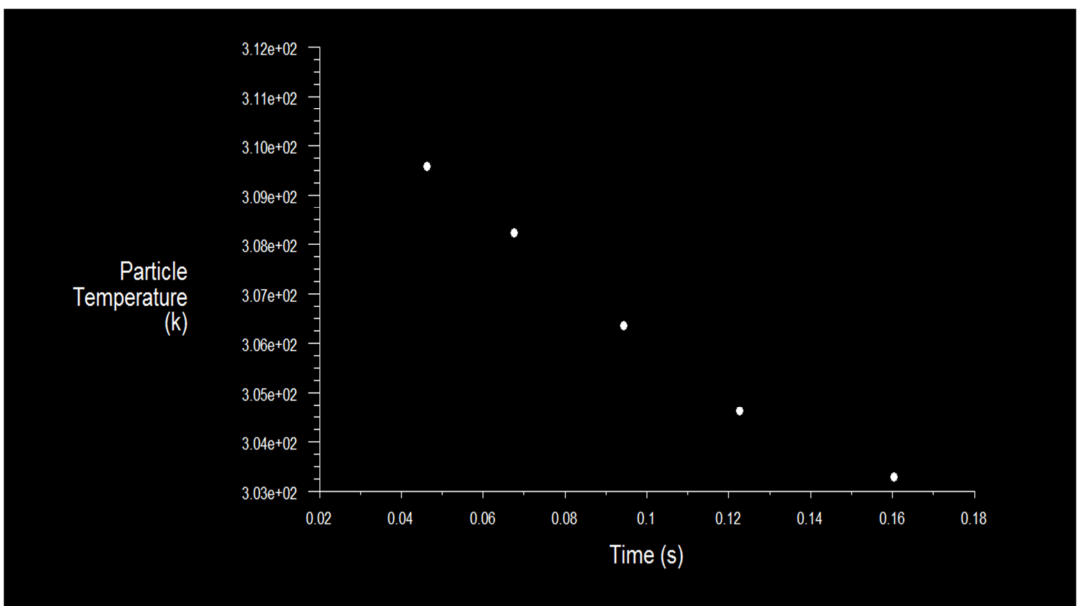

Fig: 5.31b Water temperature variation plot for fill zone at 298 K inlet air temperature

Fig: 5.31b represents temperature vs. time variation. It shows the temperature of water is decreasing up to 303.2 K.

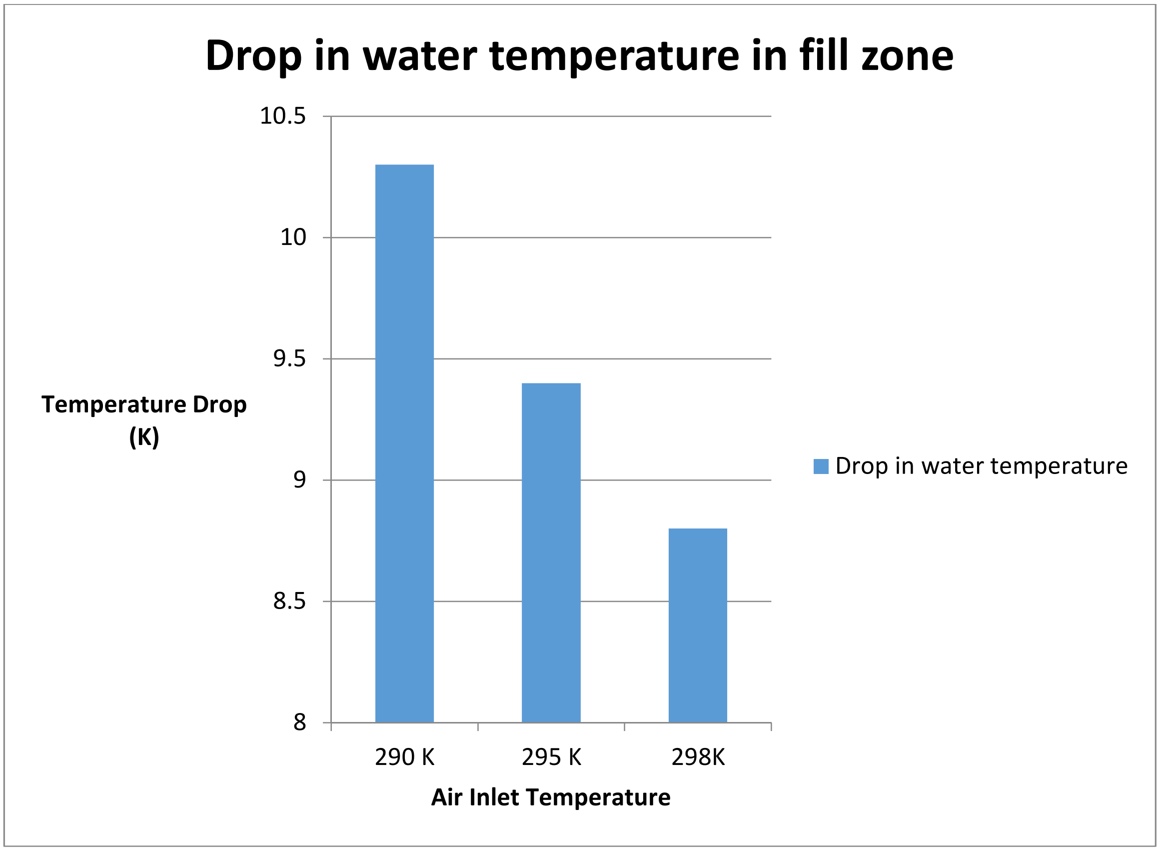

Fig-5.31 Effect Of Air Temperature In Fill Zone

The air temperature also causes a sufficient effect on cooling tower performance. It is clear from the analysis that the relative contribution of rain zone and fill zone remains almost same irrespective of air temperature. However the relative cooling load is decreasing in fill zone for higher air inlet temperatures. The cooling load in the fill zone is decreasing from approximately 74% for 290 K to 72.5% for 298 Kelvin air inlet temperature.

5.6 EFFECT OF AIR TEMPERATURE ON COOLING IN RAIN ZONE-

CASE 1-

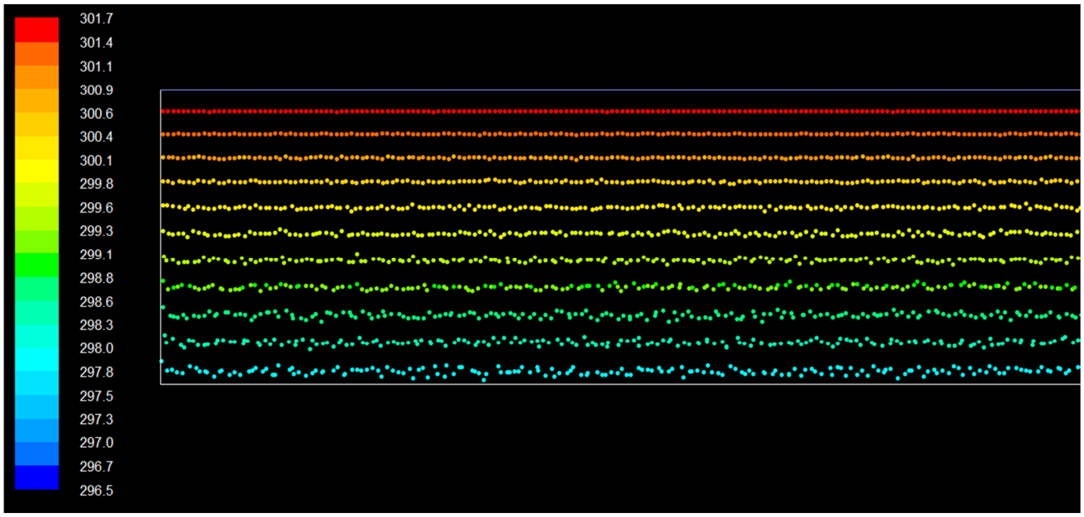

Fig: 5.32a Water temperature variation for rain zone at 290 K inlet air temperature

Fig: 5.32a shows the temperature variation in the rain zone of the cooling tower having a height of 7.127 meter. In this picture the water temperature is decreasing up to 298.1 K.

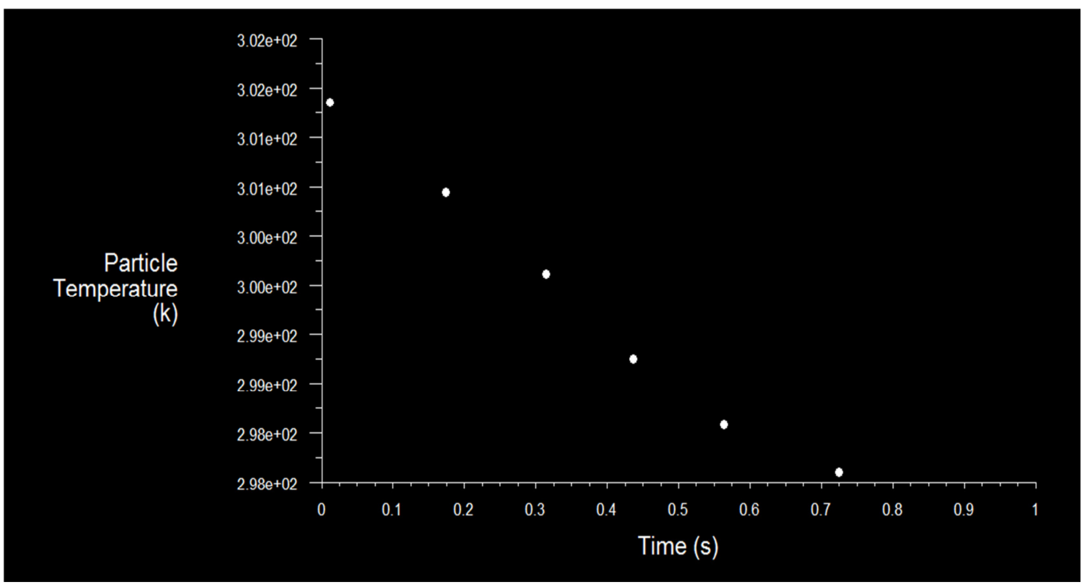

Fig: 5.32b Water temperature variation plot for rain zone at 290 K inlet air temperature

Fig: 5.32b represents temperature vs. time variation. It shows the temperature of water is decreasing up to 298.1 K.

CASE 2-

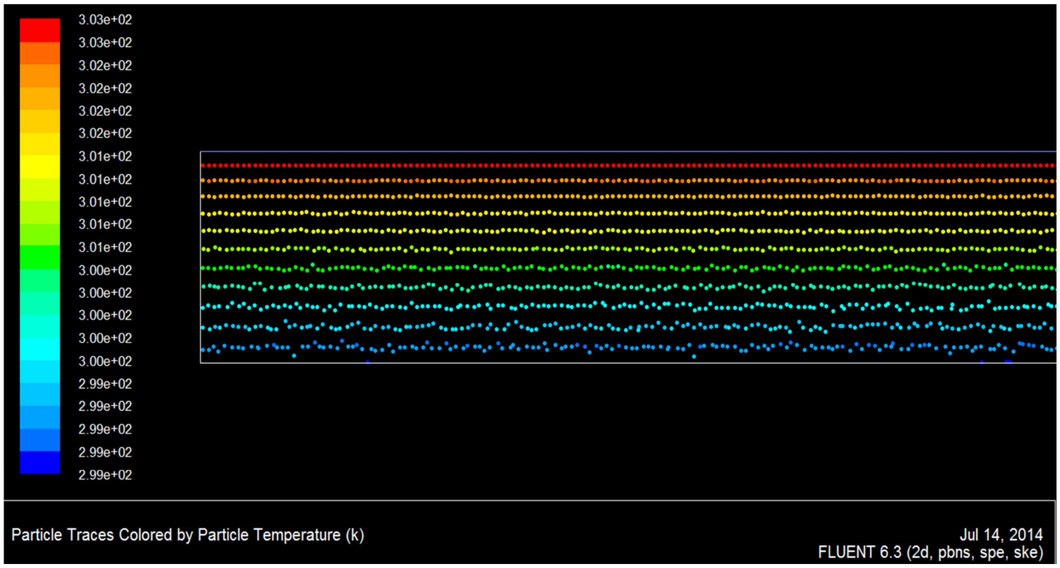

Fig: 5.33a Water temperature variation for rain zone at 295 K inlet air temperature

Fig: 5.33a shows the temperature variation in the rain zone of the cooling tower having a height of 7.127 meter. In this picture the water temperature is decreasing up to 299.1 K

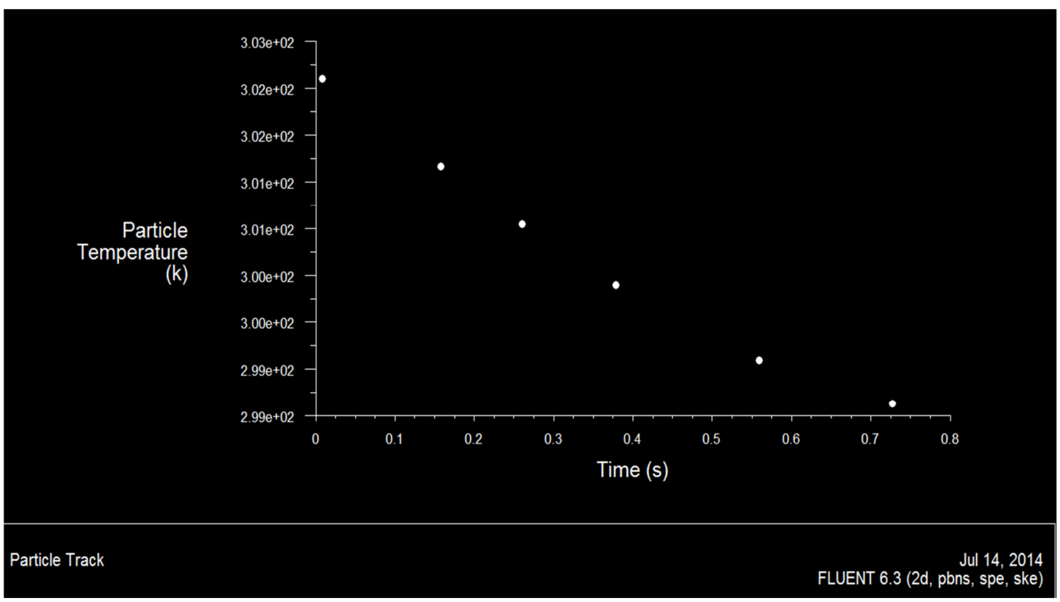

Fig: 5.33b Water temperature variation plot for rain zone at 295 K inlet air temperature

Fig: 5.33b represents temperature vs. time variation. It shows the temperature of water is decreasing up to 299.1 K.

CASE 3-

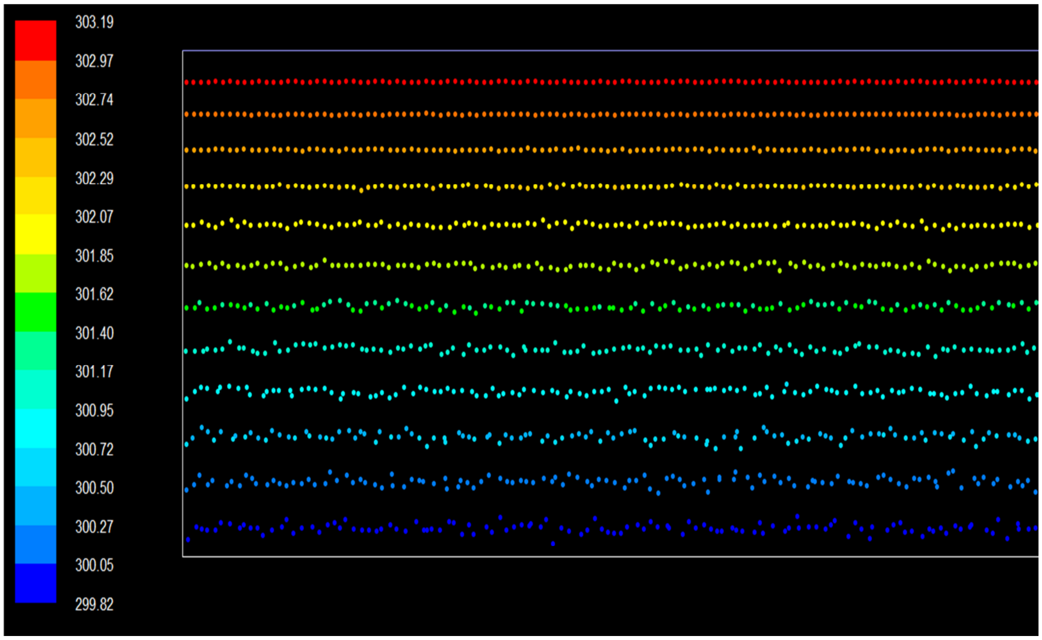

Fig: 5.34a Water temperature variation for rain zone at 298 K inlet air temperature

Fig: 5.34a shows the temperatures variation in the rain zone of the cooling tower having a height of 7.127 meter. In this picture the water temperature is decreasing up to 299.9 K.

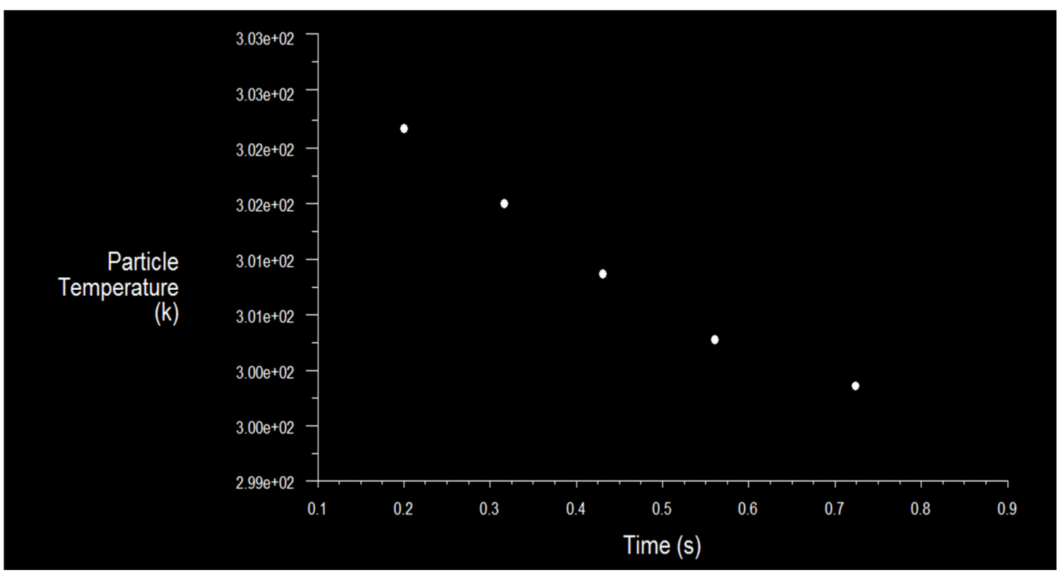

Fig: 5.34b Water temperature variation plot for rain zone at 298 K inlet air temperature

Fig: 5.34b represents temperature vs. time variation. It shows the temperature of water is decreasing up to 299.9 K.

The variation in cooling in the rain zone and the fill zone is recorded for the cooling tower inlet height of 8.577 m. height and the fill depth of 1 m. The other conditions are kept same as that for reference cooling tower. This variation is seen for three different air temperatures i.e. at 290 K, 295K and 298 K. The relative contribution for the cooling in the rain zone increases as the air temperature is decreased and so the less relative percentage cooling happens in the fills.

From the diagram shown below it is clear that the relative contribution of rain zone and fill zone remains almost same irrespective of air temperature. However the relative cooling load is decreasing in fill zone for higher air inlet temperatures. The cooling load in the fill zone is decreasing from approximately 74% for 290 K to 72.5% for 298 Kelvin air inlet temperature.

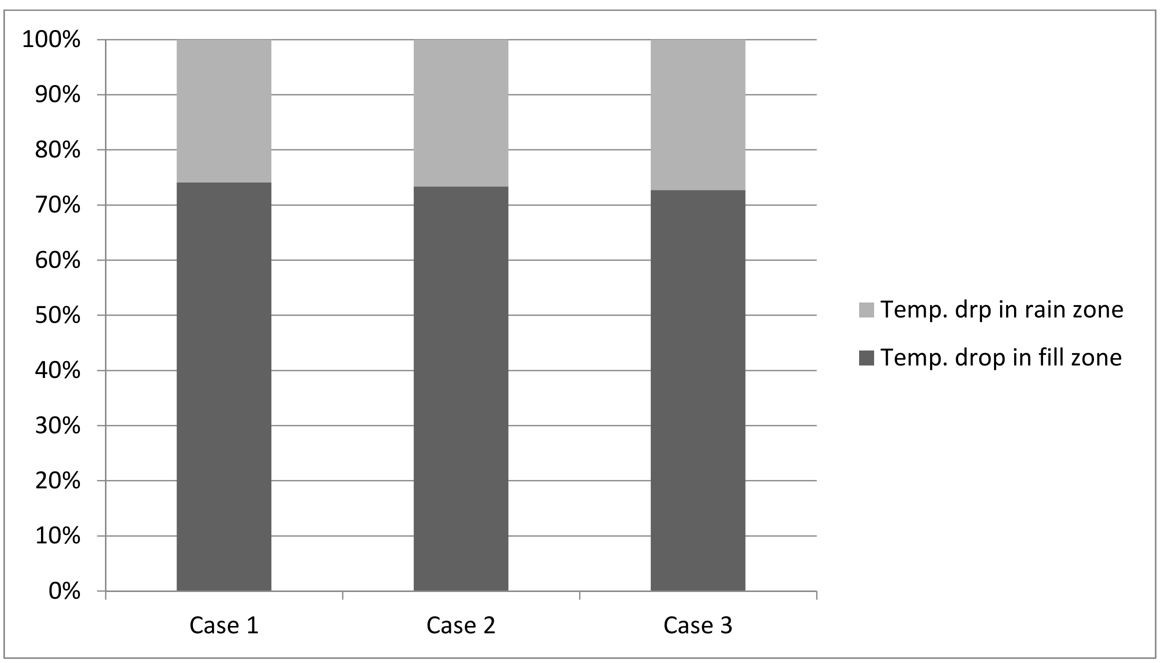

Fig: 5.35-Cooling contribution of different zones for variable air temperature

5.7 CONCLUSIONS

The following conclusions are drawn on the basis of the analysis done in this present thesis.

1. The higher fill depth causes a higher water temperature drop. This rate of improvement in cooling decreases for the higher fill depth.
2. The cooling in rain zone increases for the higher height of fill zone. The result shows that the degree of cooling decreases as the rain zone height decreases which is primarily due to two reasons the first is that for a lower height the residence time of droplets is low and the second is because of the lower difference in the saturation pressure and the vapor pressure which is the driving force for vaporization.
3. The performance of the cooling tower degrades for higher flow rates of water. Relatively less water cooling is observed in fill zone as well as in rain zone. This is because of less air available per unit mass of water and so the less diffusion and low heat transfer is accountable for this phenomenon. The sufficient evaporation in this condition is not possible because air will now get more humid early.
4. The air temperature also causes a sufficient effect on cooling tower performance. It is clear from the analysis that the relative contribution of rain zone and fill zone remains almost same irrespective of air temperature. However the relative cooling load is decreasing in fill zone for higher air inlet temperatures. The cooling load in the fill zone is decreasing from approximately 74% for 290 K to 72.5% for 298 Kelvin air inlet temperature.

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