



*Research Paper*

# PERFORMANCE ANALYSIS OF SINGLE SLOPE SOLAR STILL

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Solar still is the one of the cost effective method of producing pure water using solar distillation techniques. Solar still uses heat energy as input which is obtained from solar radiations. In this paper the condensation and evaporation process in solar still is developed using Computational Fluid Dynamics (CFD) method, a two phase three dimensional model is developed for simulation. Simulation result is compared with actual experimental data of solar still. There is a good agreement between experimental data and CFD data of fresh water productivity, water temperature and heat transfer coefficients. Study shows that CFD is a powerful tool for the performance analysis of single slope solar still.

Keywords: Single slope solar still, CFD

## INTRODUCTION

Now days, lack of drinking water is majour problem in most of the countries. Most of the water resources are under the stage of depletion. Solar still is an economical and easy method for production of pure water. Evaporation and condensation are the basic principles used in solar still. The impure water in the solar still is heated by solar radiations that penetrate through the glass cover this causes water to evaporate. Due to temperature difference between water and glass cover the water starts condensing at glass cover leaving all contaminants in the basin.

An extensive review paper of solar stills has been published by Hitesh and Shah (2011) conducted experiments using different glass cover thickness and concluded that lower glass cover thickness increases distillate output from solar still. Tiwari and Tiwari (2006) conducted an experiment using three condensing surfaces inclined at 15°, 30° and 45° to determine the relation for calculating convective and evaporative heat transfer coefficient under indoor conditions. Jadav (2011), used Black granite as basin material inside single slope solar still and compared with iron steel basin of solar still. He proved that, average productivity of black granite basin

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solar still is 3.784 L/m<sup>2</sup> day and iron steel basin is 2.358 L/m<sup>2</sup> day, means 38% more. Omar (2011), used active solar single slope solar still using different operational parameters like different insulation thickness, solar intensity, effective absorptivity and transmissivity theoretically and compared with experimental data to choose best factor enhancing solar still productivity. Dunkle (1961) has given a semi empirical relation for internal heat and mass transfer coefficient to predict the hourly and daily yield for different solar still design. Jeremy (2011) concluded that Both computer-aided modeling/simulation and prototype testing show the reliable function of this solar still system design. Pankaj and Agrawal (2012) concluded that the black lined solar still operates at higher temperatures as compared to white lined still and since the temperature difference between basin water and glass cover is higher than that of the white lined still, higher distillate output is obtained in the former.

In this paper, a 3-dimensional two phase model was developed for condensation and evaporation process in single slope solar still using ANSYS CFX and the simulation result is compared with experimental data. Comparison includes fresh water production rate, water temperature and heat transfer coefficients.

## MATHEMATICAL MODEL

In solar distillation systems, heat transfer can be classified in to two types, internal heat transfer and external heat transfer. In external type heat transfer is due to conduction, convection and radiation processes which are independent of each others. The heat transfer taken place within the solar still is called internal

heat transfer which is mainly due to convection, radiation and evaporation. Performance of a solar still is directly depends on the internal heat transfer and fresh water production rate.

Density difference of humid air due to temperature difference inside the solar still is the major reason for convective heat transfer. Badran (2007) relation for convective heat transfer coefficient ( $h_{cw}$ ) is employed

$$h_{cw} = 0.884 \left[ T_w - T_g + \frac{(P_w - P_g)(T_w + 273)}{268.9 \times 10^3 - P_w} \right]^{1/3}$$

where,

$$P_w = \exp \left( 25.317 - \frac{5144}{T_w + 273} \right)$$

$$P_g = \exp \left( 25.317 - \frac{5144}{T_g + 273} \right)$$

Due to solar radiation water get heated and evaporated. The evaporative heat transfer ( $h_{ew}$ ) from water to glass is given by:

$$h_{ew} = 16.27 \times 10^{-3} \times h_{cw} \times \frac{(P_w - P_g)}{(T_w - T_g)}$$

The radiation heat transfer coefficient ( $h_{rw}$ ) from water to glass is given by

$$h_{rw} = v_{effective} \uparrow \left[ (T_w + 273)^2 + (T_g + 273)^2 \right] (T_w + T_g + 546)$$

where,

$$\uparrow = 5.669 \times 10^{-8} \text{ W/m}^2\text{K}^4$$

$$v_{effective} = \left( \frac{1}{v_g} + \frac{1}{v_w} - 1 \right)^{-1}$$

$$v_g = v_w = 0.9$$

Total heat transfer coefficient ( $h_{total}$ ) from water to glass is given by:

$$h_{total} = h_{cw} + h_{ew} + h_{rw}$$

Hourly yield of solar still is given by

$$m_w = \frac{q_{ew} A_w}{L} \times 3600$$

## EXPERIMENTAL SET UP

Figure 1 shows the experimental set up of solar still. It consists of basin liner which is the major part of solar still. It absorbs incident solar radiations that are transmitted through the glass cover. Basin liner is made of GI sheet of 1mm thickness and it has an area of 1 m × 0.5 m with lower vertical side height of 0.30 m and higher vertical side height of 0.39 m. The heat losses from bottom and side walls of solar still is prevented by using term cool and plywood materials. Condensing cover of solar still is made of glass of 4 mm thickness and it is placed on vertical walls of solar still at an inclination of 10°. The condensed water get collected in a distillate channel. A plastic pipe is connected to distillate channel to drain distillate water to measuring jar and a drainage pipe is connected to remove wastes inside the solar still. Rubber gaskets are provided between glass cover and vertical walls to prevent heat loss. Thermocouples are fixed in to the solar still to measure basin liner, glass and water temperature and these thermocouples are connected to a digital temperature indicator to indicate the reading.

## FLOW GEOMETRY

Computational Fluid Dynamics (CFD) is one of the branch of Engineering, Finding numerical solutions of governing equations,

Figure 1: Experimental Set Up of Solar Still



using high-speed digital computers. ANSYS CFX is simulation software based on CFD technique. Figure 2 shows a 3-dimensional model of single slope solar still using ANSYS CFX 13 and Figure 3 shows the mesh of the model.

## Boundary and Initial Conditions

To simulate the condensation and evaporation process in solar still appropriate boundary conditions must be specified at each boundary. The recorded experimental data are for 7 h, starts from 9.30 am to 4.30 pm. CFD simulation run time of 7 h that is required for

Figure 2: Model Geometry of Solar Still

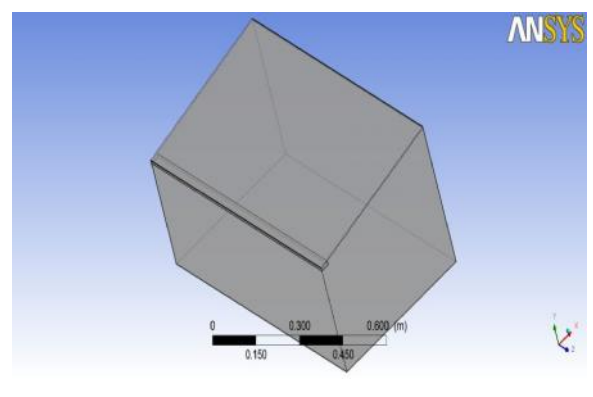
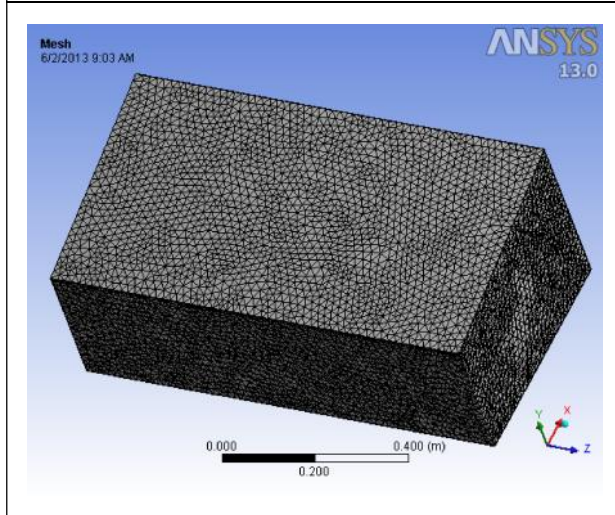


Figure 3: Mesh of Model



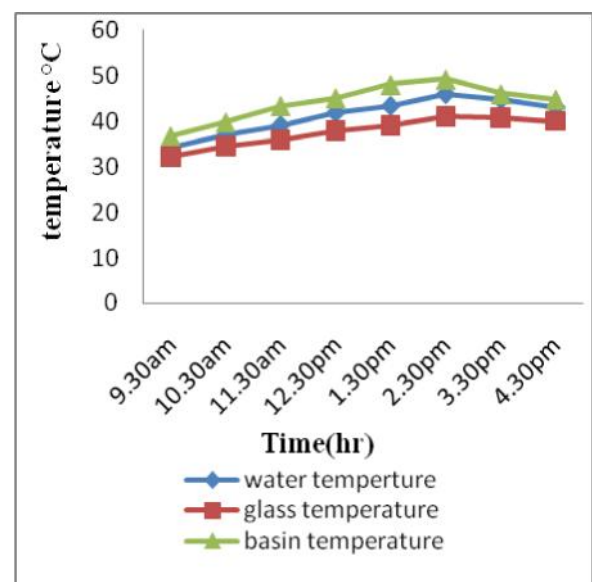
modeling of solar still which is an unsteady state process is impossible due to high number of time steps and computer time limitations.

Hence in order to overcome this problem it was assumed that steady state condition is reached after a time interval of 1h and received water, glass temperature and basin temperature are almost constant. Hence the overall simulation process was modeled as 7 stages of 1 h interval in a quasi steady state condition. A two phase domain is created in VOF frame work for liquid water and mixture of water vapour and air. Evaporation process is modeled as laminar at quasi steady, accounting for thermal energy heat transfer while considering the effects of buoyancy. Due to distinct interface between liquid and vapour phase, both phases are assumed to be continues. Two resistance model is taken to transfer the heat, zero resistance model for gas phase and heat transfer coefficient for water phase. It was assumed that bottom temperature is equal to water bath temperature and distillate collector temperature is equal to

glass temperature. Adhesion forces are taken for drop formation in condensing cover. All sides are assumed adiabatic so there is no heat loss to surrounding. No slip boundary condition is specified for liquid phase and free slip boundary condition is specified for vapour phase.

Glass temperature, water temperature and bottom temperature are taken according to experimental data is shown in Figure 4. Intially water level in the basin is taken as 80 mm so the water and gas mixture volume fraction are taken as 0.24 and 0.76.

Figure 4: Temperature Variation of Different Elements in Solar Still



## SIMULATION RESULTS

ANSYS CFX 13 software is used for CFD analysis. Building model geometry and its meshing were done using ANSYS Workbench 13. Unstructured mesh of type tetrahedral was used. The sensitivity of the simulation results to grid size was checked. For lowering computational efforts and for getting closure

simulation and experimental results simulation is carried out with 45669 nodes.

Due to solar radiation water gets heated and vaporizes. The temperature difference between water vapour and glass leads to condensation of vapour in glass surface. The condensed water droplets slide down and get collected in distillate channel. The amount water collected in channel is considered to be the fresh water production rate. Figure 5 shows the mass flow rate along a plane inside the solar still. This mass flow rate is used to calculate the rate of fresh water production. Figure 6 shows the result of simulation run and experimental data in a 7 h time period. From the figure it can be noted that as the time passes water in still get heated by solar radiation. Gradually the still space saturates with water vapor and the freshwater production rate increases until about 2.30 pm. After that by decreasing solar radiation, produced water amount comes down slowly.

Figure 5: Water Mass Flow Predicted by CFD Simulation

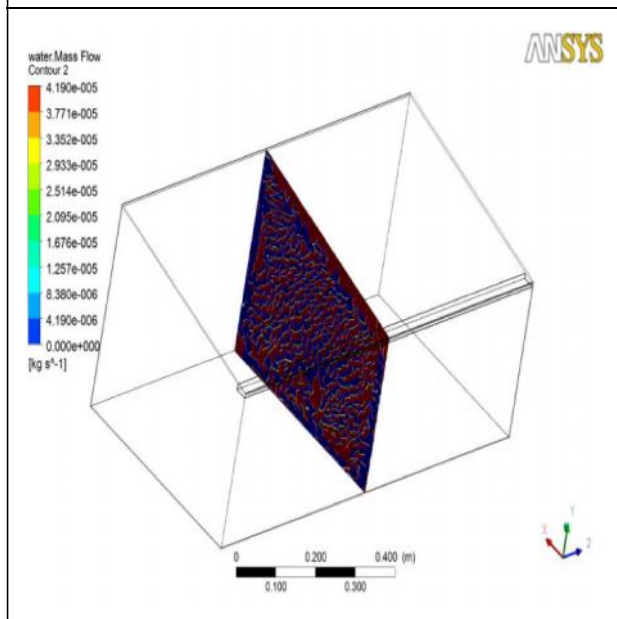
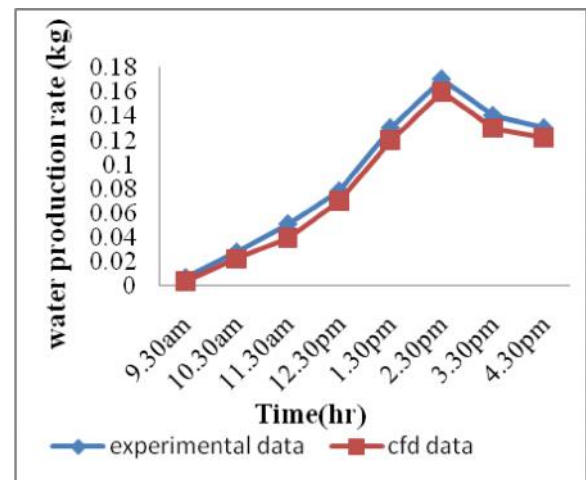


Figure 6: Fresh Water Production Rate from Experimental Data and CFD Data



Water temperature predicted by CFD simulation is shown in Figure 7.

Water temperature predicted by CFD simulation is compared against experimental data is shown in Figure 8.

Difference between experimental data and simulation data is called error. From Figure 6 and Figure 8 average percentage of error for

Figure 7: Water Temperature Contour of Solar Still

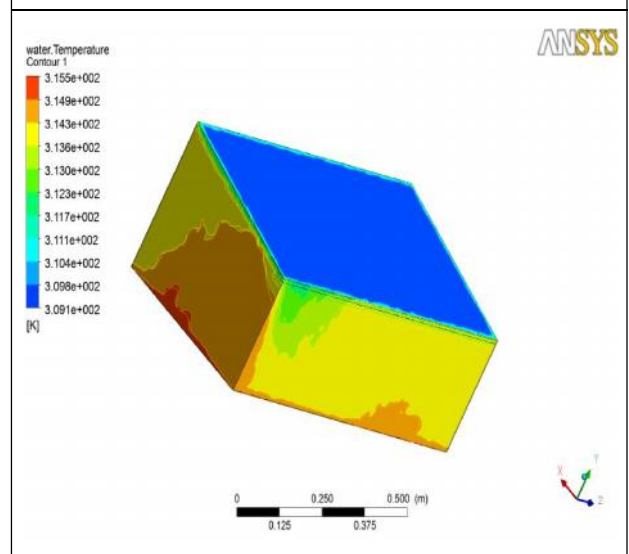
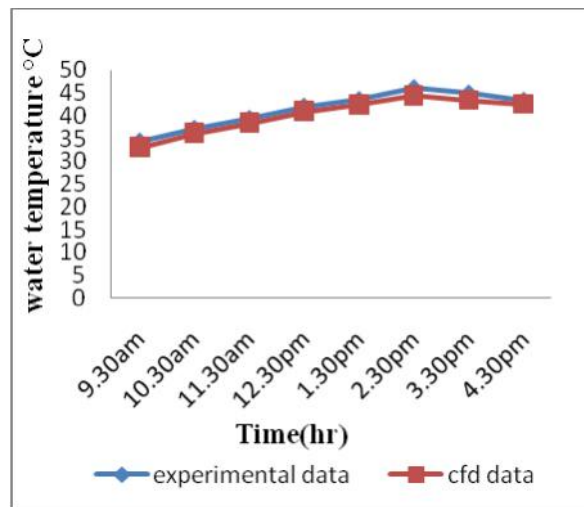




Figure 8: Water Temperature Predicted by the CFD Simulation and Experimental Data



fresh water production and water temperature are 15% and 2.57%.

Water droplets condensed on glass is shown in the Figure 9. Figure 10 shows the water volume fraction contour corresponds to distillate channel.

Temperature contour of gas mixture is shown in Figure 11.

Figure 9: Water Volume Fraction on Glass Cover

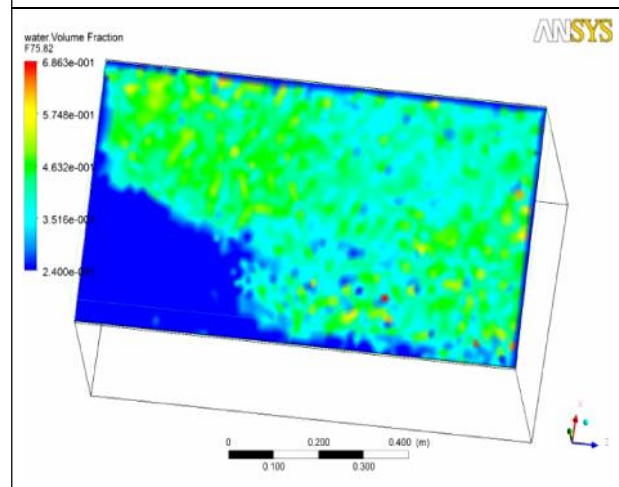


Figure 10: Water Volume Fraction Contour on Distillate Channel

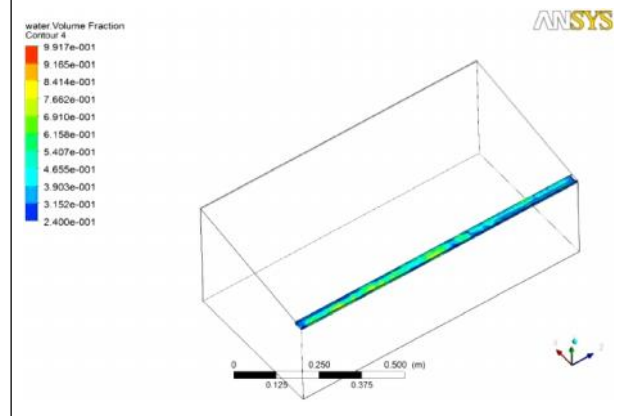
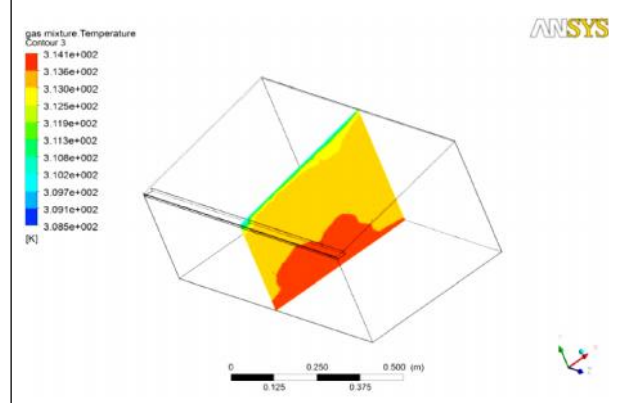
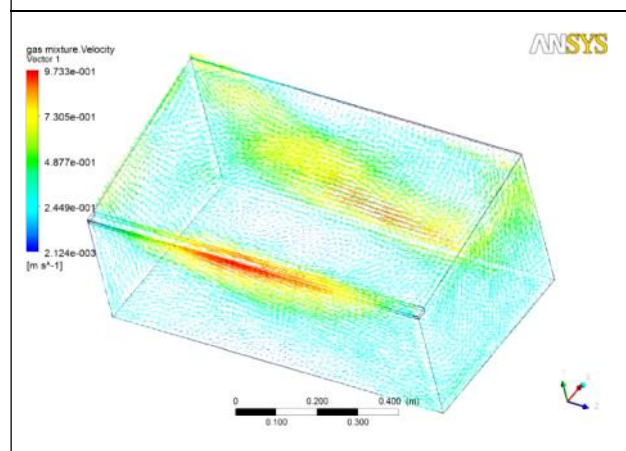


Figure 11: Gas Mixture Temperature on a Plane Inside Solar Still



Gas velocity vector on solar still is shown in Figure 12. Gas phase moves in circular path

Figure 12: Gas Mixture Velocity



lines, due to effect of buoyancy force warm phase move upwards and condensed on glass cover.

Figures 13 and 14 shows the variation of evaporative and convective heat transfer coefficient from experimental and CFD data. The average errors for evaporative and convective heat coefficient are 5.5% and 3.01% respectively.

Figure 13: Variations of Evaporative Heat Transfer Coefficient

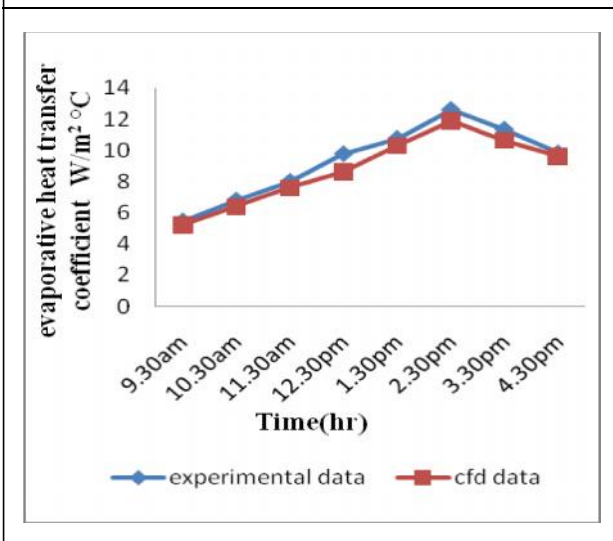
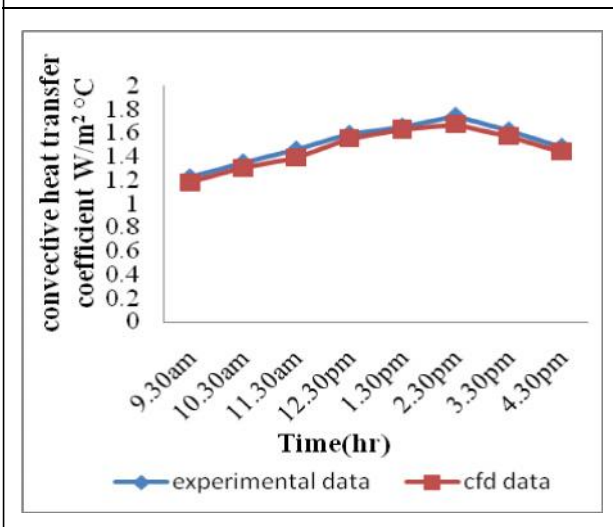


Figure 14: Variations of Convective Heat Transfer Coefficient



## CONCLUSION

Here a two phase three dimensional model is made for evaporation and condensation process in solar still by using CFD techniques. There is good agreement between simulation result and experimental result with certain errors. The results predicted by ANSYS CFX show that, it is very powerful tool for design, parameter analysis and difficulty removal in solar still construction. ☺

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## APPENDIX

| Abbreviations and Symbols |   |
|---------------------------|---|
| $A_w$                     | Evaporative surface area, m <sup>2</sup>                                      |
| $h_{cw}$                  | Coefficient of convective heat transfer, W/ m <sup>2</sup> °C                 |
| $h_{rw}$                  | Coefficient of radiative heat transfer, W/m <sup>2</sup> °C                   |
| $h_{ew}$                  | Coefficient of evaporative heat transfer, W/m <sup>2</sup> °C                 |
| $h_{total}$               | Total heat transfer coefficient from water to cover, W/m <sup>2</sup> °C      |
| $L$                       | Latent heat of vaporization, J/kg   |
| $m_w$                     | Fresh water production rate, kg   |
| $P_g$                     | Partial saturated vapor pressure at glass cover temperature, N/m <sup>2</sup> |
| $P_w$                     | Partial saturated vapor pressure at water temperature, N/m <sup>2</sup>       |
| $T_b$                     | Temperature of basin, °C  |
| $T_a$                     | Ambient temperature, °C   |
| $T_g$                     | Temperature of glass, °C  |
| $T_w$                     | Temperature of water, °C  |
| $q_{ew}$                  | Heat transfer rate due to evaporation, W/m <sup>2</sup>                       |
| $q_{rw}$                  | Heat transfer rate due to radiation, W/m <sup>2</sup>                         |
| $q_{cw}$                  | Heat transfer rate due to convection, W/m <sup>2</sup>                        |
| $CFD$                     | Computational fluid dynamics  |
| <b>Greek Symbols</b>      |   |
| $\nu$                     | Emissivity  |
| $\dagger$                 | Stephan boltzman constant, W/m <sup>2</sup> K <sup>4</sup>                    |