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Experimental study on cooling of solar collectors using air-water mixture

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Abstract

Large numbers of studies are reported on solar collectors using a single fluid to cool it, be it with water or with air only. The present paper reports a series of experiments that investigate into the performance of solar collectors that are cooled by an air-water mixture, a two-phase heat transfer fluid. This special way of cooling of solar collectors is designed in conjunction with a humidification-dehumidification cycle that produces hot water and saturate air at the same time to run an efficient solar distillation unit. Parameters analyzed in the study include the effects of the air-to-water ratio and the inner diameters of the absorber tubes of the solar collector. A mechanism to control air-water ratio was also developed in the process. The results indicate that the two-phase flows can efficiently cool solar collectors producing better cooling of absorber plates of solar collectors, under suitable operating conditions.

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Keywords: Venturi aerator; Solar collector; Absorber cooling; Two-phase flow.

1. Introduction

Water scarcity, especially in the developing world, demands urgent development of inexpensive, decentralized, small-scale desalination systems, powered by sustainable sources of energy, like solar energy. Countries which have abundant solar irradiation are the ones that usually face the water scarcity especially during summer. Large numbers of studies are undertaken around the globe to exploit this water-energy nexus: making use of availability of solar energy to solve formidable problem of water scarcity. Humidification-dehumidification systems (HDH) stand out as a promising solution, in which air is first humidified at high temperatures, which is then dehumidified at lower temperatures to retrieve the water contained in it, a kind of artificial rain. Efficiency of HDH cycle process depends heavily on the difference on the operating temperatures. Absorber cooling using two-phase air-water mixture is

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expected to solve the problem.

The system under study is initially planned to be driven entirely by natural forces like gravity and buoyancy. The air-intake is facilitated by pressure drops developed inside the inlet tubes due to Bernoulli Effect. A Venturi aerator, working based on the Bernoulli Effect is used to suck the air from the ambient into the water flowing down from an overhead tank under gravitational potential. The air-water mixture thus produced flows through the absorber tubes of the solar collector, cooling it. The two-phase flow is expected to improve cooling of the absorber plates, due to the turbulence produced by the air-bubbles moving along with the flow.

Further, the rate of fouling of the tubes carrying brackish water through the absorber of solar collector is expected to reduce considerably due to the presence of ever turbulent flows through the tubes. Large numbers of studies are reported recently on non-conventional collectors using organic fluid, refrigerant and nano-fluids as heat transfer fluids, with expected like corrosion prevention, high heat transfer coefficient, system efficiency and protection against freezing [1-4]. It is found that heat transfer coefficients can be enhanced by the two-phase flows at low wall heat flux or the wall superheat condition. The studies by Jie Yi et al. used a simplified two-phase flow boundary layer model to calculate the evaporative heat transfer characteristics of the annular two-phase flow of air–water [5]. From experiments they concluded that heat transfer coefficients for annular two-phase flow of air-water mixture could be enhanced by an order of magnitude compared with the single-phase air flow at the same air Reynolds. Vlasogiannis et al. [6] worked on a plate heat exchanger and tested the system under two-phase flow conditions by using an air-water mixture as the cold stream. The heat transfer coefficient of air-water stream is always higher than that of the corresponding water flow but with no air, for different air velocities tested. Zimmerman et al. [7] conducted a study of the flow pattern and heat transfer to air–water annular flow in a horizontal pipe. The results predicted the pipe wall temperature for the heat transfer to air–water flow in a horizontal tube, for a range of flow velocities.

These previous works underscores the importance of aeration of the water in enhancing flow and heat transfer performance. In general, the effect of aeration on hydraulic structures is experimentally studied by a number of investigators. However, there are not many studies on Venturi aeration so far. Venturi system creates a negative pressure at the inlet of Venturi tube due to the pressure difference associated with the differences in flow velocity. In other words, as water flows through a Venturi tube, due to flow constriction the velocity assumes higher values leading to pressure drop that result in suction pressure at Venturi throat. As [8] indicates, Venturi tubes require less than 20% pressure difference to initiate suction and hence are highly efficient. Baylar et al. [9] studied the effect of varying angles of converging and diverging cone and outlet lengths on the air-entrainment in a Venturi nozzle in a plunging water jet aeration system. They found that the increase in outlet length decreases the air entrainment into the Venturi tube.

Panthalookaran et al. [10] has proposed a novel humidification-dehumidification system, facilitated by solar collector. It consists of a solar still, working based on the humidification-dehumidification cycle in order to efficiently harvest solar energy at the solar collector, whose efficiency could be improved by cooling the collector based on water and air as the heat transfer fluids.

Irrespective of large number of experimental as well as theoretical studies on cooling solar collectors, their cooling using a two-phase fluid, namely air-water mixture, has received least attention. Similarly, there exists not study so far that reports a mechanism of controlling air-to-water ratio using a Venturi tube without needing a external valve.

The current paper reports experiments to attach the Venturi tube to aerate water that flows through the absorber tubes of a solar collector, which is expected to improve the solar heat harvest. Development of a natural mechanism to control the air-to-water ratio of the two-phase mixture using a Venturi tube constitutes an important part of the current study. The paper identifies a method to control air-to-water ratio suitable to optimally cool the absorber plates of the solar collectors and to produce hot and saturate humidified air. The end products of the collector cooling are hot and saturated air as well as hot water. Hot water thus produced could be aerated further to obtain more hot and humidified air that could be dehumidified to produce fresh water. The novel solar distillation unit is designed for domestic drinking water problems in sub-tropical wet climate zones, where solar energy and brackish water are abundantly available. The system is designed especially to summer stagnation of solar collectors in order to improve the overall efficiency of the solar collectors in the yearly cycle. It also lays special emphasis on reducing the number of moving parts in the system and controlling the flow by natural phenomena.

Nomenclature

D_1	inlet diameter of Venturi (mm)
D_2	diameter of Venturi hole (mm)
D_3	exit diameter of Venturi (mm)
D_4	diameter of throat (mm)
ID	internal diameter of the tube (mm)
Q_a	air flow rate (ml/s)
Q_w	water flow rate (ml/s)
P_{atm}	atmospheric Pressure (Pa)
β	tilt angle ($^{\circ}$)

2. Experimental set up

The experimental set up consists of production of air-water mixture using a Venturi aerator, which is passed through the absorber tubes of a solar collector to study the improvement in the heat removal from the solar collector. Water is stored in the overhead tank maintained at constant pressure head at a height of 2.81m from the ground level. Water is allowed to mix with air to form two-phase mixture of air and water, as shown in Fig. 1. The two-phase mixture of slug flow pattern passes through absorber tubes of collector, cooling it and thereby producing a mixture of hot water and hot and humid air. The collector is tilted towards south at an angle equal to optimum tilt angle of location (yearly optimum tilt angle of Kochi in India, the place of experiment, is 10°) to maximize solar harvest. The temperatures are logged and recorded at inlet and outlet collector and air and water flow rates are measured at collector outlet respectively.

2.1. Solar collector simulation

The working of solar collector is simulated in the laboratory using a flat plate having cross section area 0.27 m^2 (600mm X 450mm) and Nicrome-wire heater, which is uniformly distributed throughout the area to provide uniform heating of the plate. The heating-coil is covered by a stainless steel plate of thickness 2mm. To reduce heat losses through the back and side surfaces, these surfaces are covered with glass wool of 10 cm thickness. The top surface of the stainless steel plate is polished to minimize the radiation loss from the surface. It is then covered with a glass sheets to produce greenhouse effects inside the system as shown in Fig. 2. The distance between the glass covering and the steel plate was fixed at 30cm to suppress natural convection currents between the steel plate and the glass cover. Pure copper tubes of circular cross section are used as riser tubes to cool the stainless steel plate. To maintain

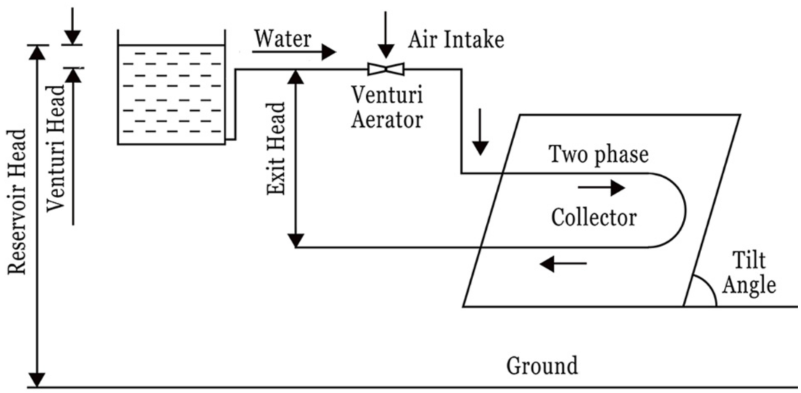

Fig. 1. Schematic of experiment setup

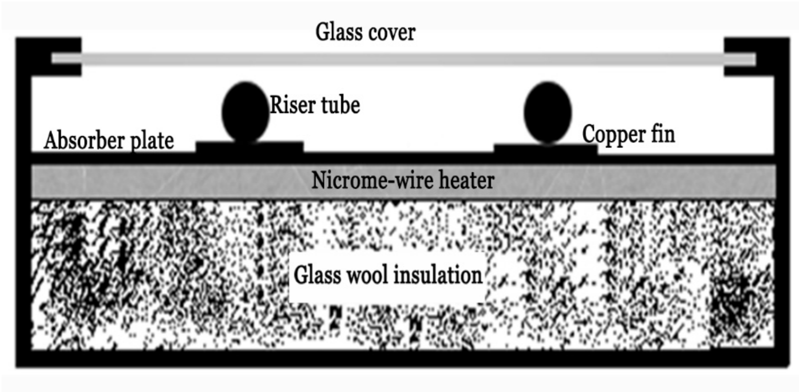

Fig. 2. Schematic of solar collector simulation

uniform surface contact area, the riser tubes are brazed to a 25mm width copper sheet of thickness 3mm and are screwed to the steel plate. The finned tubes are placed at 8 cm apart from each other. The tubes of diameter 4.5mm, 5.1mm, 6.35mm and 6.81mm are used in the experiments. A Dimmerstat was used to control the heat flux to the heater, which is monitored by a Watt meter that measure the heat input. Temperature controller is also attached to the system to warn about overheating, if any. All tubes used in the experiments were insulated with nitrile rubber insulators to avoid the losses of heat to ambient. The entire system is thus designed to simulate a solar collector that produce different thermal fluxes corresponding to different levels of diurnal solar irradiation, which is cooled by heat transfer fluids passing through the riser tubes.

2.2. Venturi aerator

The air-water mixture is generated using a Venturi aerator. The gravitational potential head of water drives the two-phase flow through the system. Venturi aerator is attractive since it does not require external power or any moving parts. The negative pressure occurring at the suction holes leads to suction of air into the pipe and is dynamically entrained into the motive system. The working of Venturi aerator is depicted in Fig. 3. In the current experiments, the inlet and exit diameters of the tube are chosen to be 5mm and throat and Venturi hole with a diameter of 4mm respectively. The ratio of inlet to hole-diameter (D_1/D_2) was fixed to 1.25.

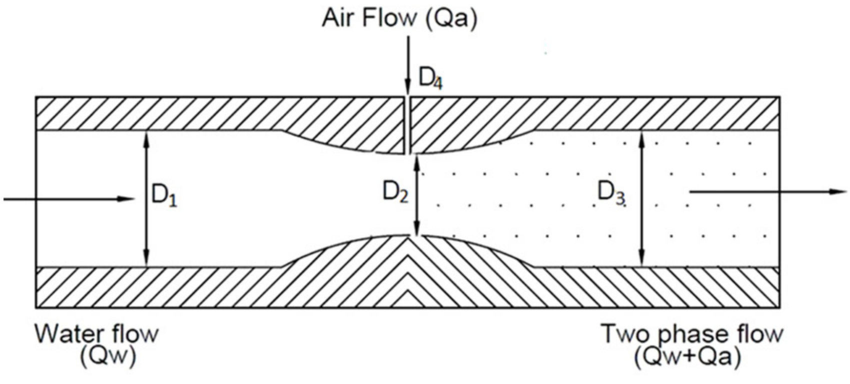

Fig. 3. Venturi aerator

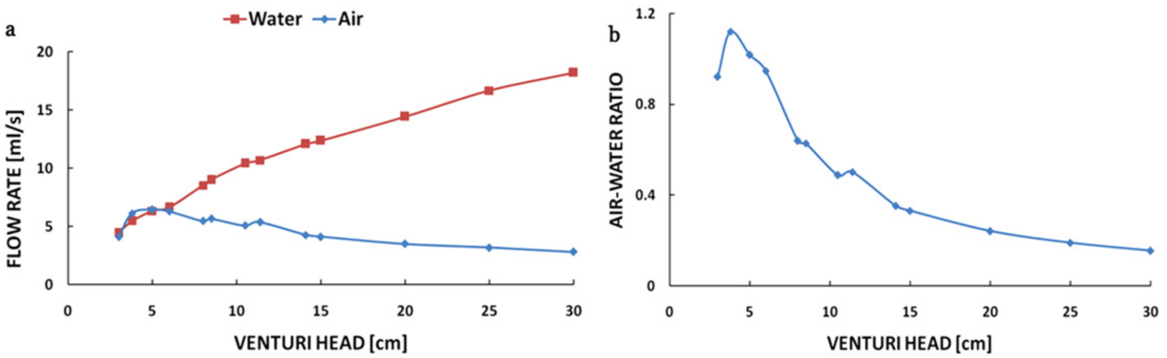

Fig. 4. (a) Venturi head vs. flow rate; (b) Venturi head vs. air-water ratio

3. Results and discussions

3.1. Control of water flow rate

Adequate control of the water flow through the tubes in the solar collector is necessary to obtain hot and humid air at the exit point to effectively run a HDH system. Velocity of the flow through a tube at a given Venturi head can be calculated by applying the Bernoulli's theorem between the reference points 1 and 2. In the current set of experiments, the reservoir head and exit head were fixed at 2.89m and 0.14m respectively. The Venturi head was systematically varied and the corresponding flow rates of air and water are measured. It is found that the flow rate of water can be effectively varied by controlling the Venturi head. The flow rate of water depends only on the Venturi head with negligible effects on the air flow rate as shown in Fig. 4. (a). Since the point 2 on Venturi is open to atmosphere the flow of water from the reservoir happens only due this head difference. As the flow rate of water increases, the air flow remains almost steady. Air-to-water ratio v/s Venturi head graph as given in Fig. 4. (b). It reveals the presence of a critical point, where air flow rate is optimum corresponding to a low value of water flow rate. Since in aeration applications better air intake with lower water flow rate is desired, such critical points bear significance.

3.2. Control of air flow rate

In the air-water mixture, air with its larger values of thermal diffusivity and lower values of specific heat can be ideally used to humidification and dehumidification medium, whereas water with its high values of specific heat can be better used as a medium to store thermal energy harvested from the solar collectors. The primary purpose of air flow control is to optimize the cooling of the collector using air-water mixture and thus to help produce hot and saturated air to optimally run a HDH system. Generally, hot and saturate humid air is liable to condense better than less hot and less saturate humid air. Hence the purpose of cooling the collector using air-water mixture is to produce condensable hot and saturate humidified air that can be easily condensed to produce potable water.

It generally demands that lesser amount of water and an optimum amount of air passes through the absorber tubes, which optimally gets heated up producing better condensable hot and saturate air. An excess of water flowing through the absorber tubes may lead to insufficient hotness of the water as well as air and thus leading to inefficient HDH process. Further, the quantity and velocity of air in the absorber tubes affects the flow regime and the pattern of the flow, radically influencing the nature of turbulence developed within the tubes. The nature of turbulence and flow patterns of two-phase air-water mixture are closely related to the heat transfer coefficients between tube surfaces and heat transfer fluid. So control of flow rate of air is vital to the effective functioning of HDH system.

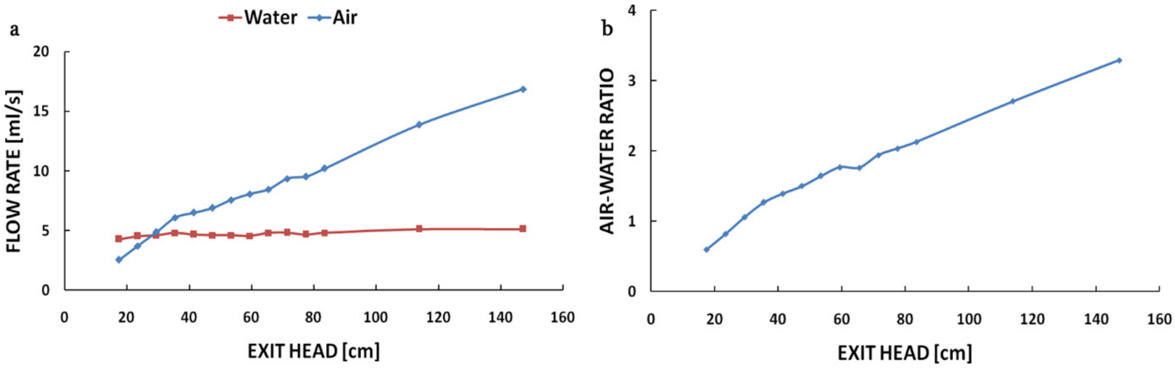

Fig. 5. (a) Exit head vs. flow rate; (b) Exit head vs. air-water ratio

The air flow rate can be controlled by varying the exit head without notable variation in water flow rate. The results leading to this conclusion are plotted in Fig. 5. (a). As already observed in Fig. 4. (a), the flow rate of air is very little influenced by Venturi head. It is rather controlled by the pressure at point 2. When this pressure, P_2 drops below the atmospheric pressure, P_{atm} air suction into the tube begins and the Venturi aerator starts.

Here different experiments are conducted at a constant Venturi head of 3cm. As the difference in pressure head with reference to the Venturi head increases, gravity is found to plays a significant role in the flow dynamics. As exit head increases, the velocity of water flow increases, which entrains more and more air into the tube. Water begins to flow with increasing velocity and in order to maintain conservation of mass, the area of cross section of the tube occupied by the water flow is reduced. The negative pressure due to the increase in velocity at point 2 on Venturi entrains more and more air into the tube as the potential head of water breaks at the opening of the Venturi aerator to the atmospheric pressure.

Fig. 5. (b) clearly suggests the enhancement of amount of air entrained into the water stream through the tubes as the exit head is increased in height. As seen in Fig. 5. (a), the amount of water flowing through the tube does not undergo considerable change with the increasing exit head. The velocity of the water flow increases with the increasing pressure head and this causes greater entrainment of the air into the tubes, effectively increasing the air-water ratio. This is an important and useful result in the design of suitable Venturi Aerator for effective HDH cycle to produce potable water resorting to solar distillation.

3.3. Airflow rate and heat harvest for different tube diameters

The next effort was to identify the influence of air-to-water ratio in improving the cooling of the solar collector or improving the solar heat harvest from the collectors. To experiment it, the water flow rate was kept constant at 0.002kg/s and the air flow rates are varied by varying the exit heads for three different absorber tubes of different internal diameters, namely, 4.5mm, 5.1mm, 6.35mm and 6.84mm respectively. All tubes were made of copper and with length, 66cm. The air-flow rates for different tube diameters for varying exit heads are plotted in Fig. 6. Temperature gain for two-phase cooling using tubes of different diameters is plotted in Fig. 7. It is found that all tubes, except the one with internal diameters (ID) 6.84mm registers an increase in temperature as the air flow increases from zero. This can only happen if the air flow creates better turbulence in the flow and thus enhancing the heat transfer coefficients of the riser tube surfaces in contact with air-water mixture. As the tube diameter increases the cooling efficiency could fluctuate, especially due to the changes in the flow pattern through the tubes. It has been observed that as the tube diameter reaches 6.84mm, the flow pattern becomes partial flows reducing the area of the tube surface in contact with the flow considerably. This is sufficient argument for reduced temperature gain for greater tube diameters. Further, the graph also shows high fluctuations probably as a result of changing flow pattern within the tube as the air velocity increases.

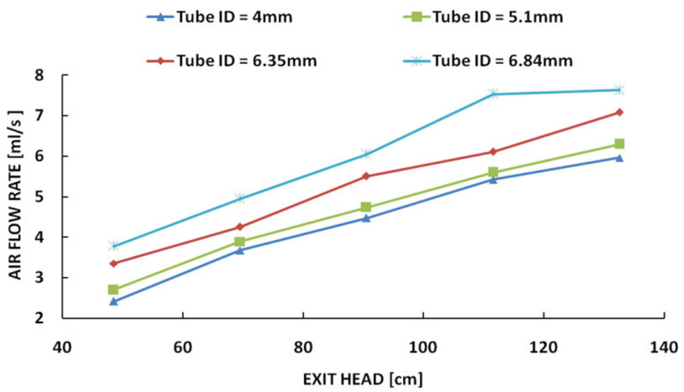

Fig. 6. Exit head vs. air flow rate for different tubes

It is also observed that as the internal diameter of the tube increases to 8mm for 0.002kg/s the two phase flow separate and a block of water column is formed, which eventually leads to the chocking of the flow on passing through the absorber plates. It is further observed that heat transfer within the tubes could be enhanced by promoting annular two-phase flow within the tubes which are at relatively low wall heat fluxes. In this case, a very thin liquid film is formed along the tube walls.

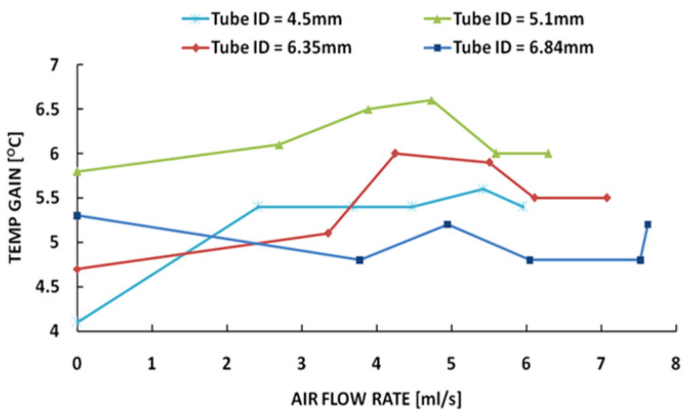

Fig. 7. Air flow rate vs. temperature gain for different tubes

4. Field test

A suitable solar collector was designed with riser tubes of inner diameter 5mm and was tested in the field conditions too. Fig. 8. shows results of a field test conducted during 10.45 AM to 2.45 PM of 28th November, 2015 at the campus of Rajagiri School of Engineering & Technology, Kakkanad, Kerala, in India. The data of solar irradiation and outlet temperatures are collected at every 30 seconds and averaged over 5 minutes each. Half of the absorber plate was cooled by the single phase water and the other half using air-water mixture. The amount of water flowing through both half sections of the collectors was made identical. In order to avoid any bias, the test was repeated by interchanging the regions cooled by the single phase water and two-phase air-water mixture alternately.

It was found that the region cooled by air-water mixture provided water in the 5-10˚C hotter than those region cooled by single phase water. Cooling by air-water mixture provided more efficient cooling the absorber plates of solar collectors at all times during the period of test. Cooling solar collectors using a two-phase air-water mixture

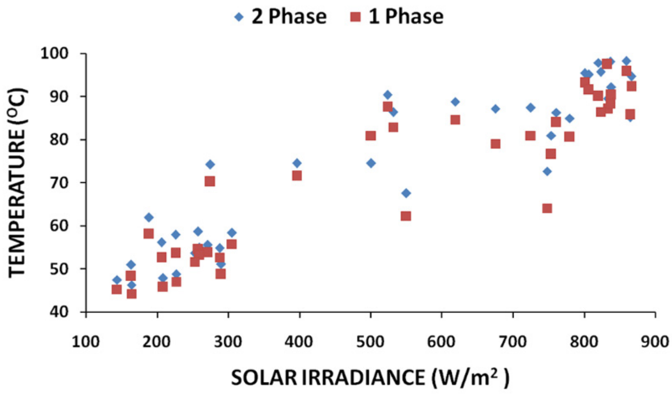

Fig. 8. Field test results

provides an edge over cooling by a single phase using water alone. This is especially suitable, when the heat transfer fluid is used to power a solar HDH cycle in conjunction.

5. Conclusions

Heat harvest from solar collectors using a two-phase mixture of air and water is experimented. The mixing of air with water is achieved by a Venturi aerator, which operates based on Bernoulli's theorem. The rate of flow of water is found to depend mainly on the Venturi head. The flow of water increased with an increase in the Venturi head, without affecting the entrainment rate of air considerably. However, the amount of air entrained was found to be controlled by the exit head, which does not on the other hand affect the rate of water flow. The velocity of water flowing through the tubes is found to increase causing larger entrainment of air into the tubes. The introduction of air into water to develop heat transfer fluid is found to work effectively under different air-water ratios through tubes of different inner diameters. Problems of chocking is experienced for larger diameters of the riser tubes and hence tubes of diameter of the order of 5mm or of lower diameters are recommended for the riser tubes used to harvest solar generated heat from the absorber plates. Both laboratory and field experiments suggested enhancement of wheat harvest from the solar collector when single phase water was replaced by two-phase air-water mixture. The air bubbles moving through the water stream is assumed to have caused turbulence in the tube flow, which in turn should have enhanced the heat transfer coefficient within the riser tubes. Further, the air-bubble moving through the tubes is expected to reduce the problem of scale formation inside the riser tubes which carries brackish water for desalination. In short, cooling of absorber tubes of solar collectors using air-water mixture is proven to be more efficient than cooling the collector using water alone, especially when the hot mixture is used to power a solar humidification-dehumidification cycle.

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