# MATHEMATICAL MODELING AND ANALYSIS OF LOW-COST PORTABLE AIR COOLER (OJRU) SUITABLE TO INDIA'S CLIMATE CONDITION

Ajit Surve
Assistant Professor, Maharashtra Academy of Naval Education and Training,
Loni Kalbhor, Pune-412201

***Abstract: In the summer when everywhere is hot environment (temperature is around 38 to 45$^0$C), most of the people suffers from the various kinds of diseases. We need to keep up the environment cool as it is our body need. Too much hot or too much cool is harmful to human body. The comfort temperature and humidity specified are 20$^0$C and 60%. The various diseases dizziness, heat stroke, headache, skin rashes, sunburns, back pain etc are common diseases where the major cause is heat. This paper explains about a portable air cooler named as "OJRU", which could be made from the available sources. It is simple and easy to make,(even in the rural or urban area) with the existing sources. The existing model which used for the experimental purpose is showing the excellent result. Suitably used for the comfort of two-three persons. The outlet temperature of the cooling system, air flow, electricity requirements etc would be calculated to get the theoretical results. The flow analysis of the same model did by using ANSYS software and compared. The result obtained could be used to change the cooling system according to available sources in the rural and urban area of India.***
***keyword: Air, humidity, dry bulb temperature, wet bulb temper- ature, cooling etc.***

## I. INTRODUCTION

*Air cooling history*

Many of us have experienced the evaporative cooling effect that occurs near a fountain at Saras Bag, Pune or in a garden on a hot day in summer. Even we enjoyed the sprinkle of Gulabpani in marriages. The sprinkle of water or cool drop of water gives us lot of relief in hot and dry region. The fountain or sprinkles inside the resident (Wada) to keep the cool climate is a kind of air cooler. The Raste Wada at Wai, Shaniwar Wada, Vishrambaug Wada at Pune or even there are many famous buildings in India or outside where such technique had used. The building cooling started in Egypt. These instruments include the use of water ponds, water pots, pools joined in various ways into thick-walled and shaded inserted to give areas that would have been cool. Hygrometer made by Leonardo da Vinci in the 16th century. It uses a wool ball to show humidity level. [1] Leonardo Da Vinci made the first Air Cooler. Air cooler had made from a water wheel, which was hollow. An air passage to guide the air had created in the water wheel. The air cooled by adding of water particles and evaporation of water. A partly submerged wheel in the water stream provided required the power difference to move the air.[2] In the 17th Century, Pascal's law: pressure exerted anywhere on a fluid at rest get transmitted without change to every part of the fluid and to the walls of the vessel.[2] Robert Boyle law: The volume varies inversely with the pressure if the temperature of gas is kept constant. Most of the Fluid Dynamics laws added by Bernoulli, Pitot, Chezy, Euler, and others. Which forms the base to develop fluid mechanics. Dalton law of partial pressure useful to know the nature of evaporation and its importance to the global cycle.[2] In the year 1856, Darcy introduced an equation that explains the flow of fluid through the porous medium. Willis Carrier developed a psychrometric chart in 20th century.[2]

*Air Coolers*

The air cooler is a system that cools the incoming hot air. The air cooling occurs as water gets evaporated. Vapor compression cycle used in the air conditioner to condition the air. The air passed over the evaporative coil. Air would be mixed and passed over water in air coolers. The heat of hot air could be used to convert water to water vapor. The temperature of the air reduced due to the transfer of heat. The electrical consumption is low as compared to air conditioners. Air coolers coalesce water particles in the air and increase the humidity in dry environment. The air took inside the cooling system. The heat of air used to evaporate the water. As the water gets the sensible heat from the air, the temperature of air drops and the air would be cooled. The heat gain from the air could be used to change the phase of water. The enthalpy of air, not changes, it remains constant. The change in temperature of incoming air depends on the drop in water temperature and humidity rise depends on latent heat gain to change the phase of water. Air coolers are more effective if relative humidity is less. The air cooler could be used in such climate, where wet bulb temperature of outside air not exceed 22$^0$C.

Perspiration - a natural evaporation: Our body sweats, if the outside temperature of air reaches above 98.6$^0$C. in dry and hot climate, sweat evaporates and take a little body heat with it. Sweat helps in cooling down in two ways (a) It makes the skin wet to feel cool and (b) when it evaporates, takes some heat from the body. In high humid climate, as more moisture in the air, sweat evaporation reduces, creating the uncomfortable condition. A fan or blower blows more humid air away from the skin so that the sweat evaporate quickly and you will feel better. But the sweat is the hydration. Our body uses a lot of water to make and evaporate the sweat to keep skin cool. So we need to drink more water on summer days, to avoid dehydration. A headache or dizziness are the common problems due to dehydration.[3] Air cooler [OJRU] blows the air at $20^0$C and 60-70 % relative humidity which will keep the skin cool. As the hydration rate reduced, you feel enthusiastic and smart. A small amount of perfume available in various flavor like mogra, kewada, jasmin etc create pleasant environment. A cooler which gives us so much in hard period, so let's name it as "OJRU" (A Marathi word 'OJRU' means god "GANESH" who has head of an elephant. Elephant takes the water in his trunk and spread it over body to keep himself cool in hot sunny days. )

Air cooling process on psychrometric chart: The process in the air cooler for condition recorded on 21.04.2017 at 11.30am. at Staff room of MANET, Loni Kalbhor, Pune is as shown on psychrometric chart in fig.1 (Blue line)

Condition:

Atmospheric dry bulb temperature=29 $^0$C (84.2$^0$F)

Outside of air cooler near fan = $20^0$C ($68^0$F) Wet Bulb Temperature =15.5$^0$C (59.9$^0$F)

Air cooling can possible by two ways,

Direct air coolers

Indirect air coolers

Direct air coolers: Purpose: lower temperature, increase humidity.

Working: Energy in the air remains constant. In this type of coolers, hot air converted to moist cool air. Incoming air heat used to evaporate water.

RH increases to 70-90 %, so feeling comfortable. Continuously the moist air exhausted to outside. Cooling fan blows out the air. Air will become saturated and evaporation will stop if not blown out.

Indirect air coolers: Purpose: Similar to the direct air coolers but uses a heat exchanger to cool supplied hot air. So less humidity. Working: The cooled moist air from the direct air coolers used to cool supplied air with a heat exchanger. No direct

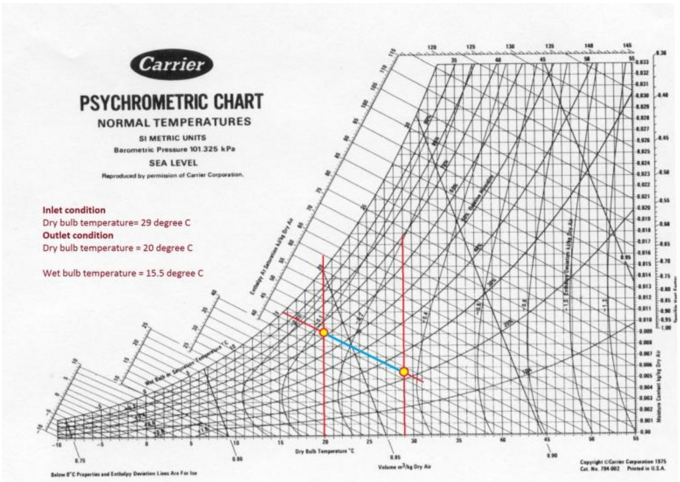


Fig. 1. Air cooling process; Psychrometry chart source-https://lehighcheme.wordpress.com/2013/11/

contact occurs between conditioned supplied air and the cooled moist air. The moist air exhausted to outside. It is used to cool other devices. This types of air coolers reduces the temperature of air and keep the humidity low.

## II. ELECTRICITY BILL

Electricity bill for OJRU Air cooler is given in Table:1,
E(kWh/day)= P(W). t(h/day) / 1000W/kW Cost(Rs/day)= E(kWh/day). Cost(Rs./kWh) Let,

For one fan of 60W power consumption, 8 hrs. use per day and for one pump 18W power consumption, 8 hrs. use per day Electricity Tariff - 6.05Rs/kWh (100-300 units)

Bill for fan = Rs.2.904/- per day or Rs. 88.39/- per month or Rs. 1060/- per year.

Bill for pump = Rs.0.8712/- per day or Rs. 26.517/- per month or Rs. 318.206/- per year.

Total bill = Rs.3.7752 per day or Rs. 114.90/- per month or Rs. 1378.8/- per year.

## III. SETUP

The photograph shows the cooler setup (fig. 2 to 6). The system needs one exhaust fan, one pump, one cabinet, aspen pads and PVC pipes etc. the real set up made and tested for air temperature near the fan outlet. It could be observed that the outlet air temperature is around 18 to 20 $^0$C, when the inlet temperature was 31.5 0C. 11 to $12^0$C temperature drop is possible.

Measuring instruments

Thermometer

The thermometer used is as shown fig.7. The range of thermometer is 0 to $100^0$C.

TABLE I
ELECTRICITY BILL

| Item | W | no. of hrs per day | Electricity Bill/month |
|---|---|---|---|
| Fan | 60 | 8 | Rs.88.39/- |
| Pump | 18 | 8 | Rs. 26.517/- |
| Total | 78 | 8 | Rs. 114.907/- |

Fig. 2. The air cooler unit: OJRU

  

Fig. 3. Top view the air cooler :OJRU

Psychrometer

Refer fig.8 and fig.9. Two types of psychrometers are used. One is a rotating type and other is a fixed type.

## IV. PERFORMANCE

Air cooling performance depends upon changes in outside temperature and humidity. "OJRU" air cooler is able to decrease the temperature by $10^0$C ($50^0$F) For direct air cooling, the saturation efficiency E related to the temperature of the leaving air. It could be defined as the ability of the cooling system to change the temperature of incoming air near to the wet-bulb temperature. The saturation efficiency could be determined as, [1],

Fig. 4. Top cover open :OJRU

Fig. 5. After adding cooling coil :OJRU

$$E = \frac{Tdo - Tdc}{Ido - Iwo} \qquad (1)$$

Where: E = Direct air cooling saturation efficiency (%)
T do = Incoming air dry-bulb temperature ($^0$C)
T dc = leaving air dry-bulb temperature ($^0$C)
T wo = Incoming air wet-bulb temperature ($^0$C) Readings taken on 13.04.2017 at 14.00pm, T do = $32^0$C T dc = $17.5^0$C T wo = 15.5 $^0$C

$$\epsilon = \frac{32 - 17.5}{32 - 15.5} = 0.8787(87.87)\% \qquad (2)$$

Air cooler efficiency varies between 75% to 95%. The efficient systems can lower the dry bulb temperature of incoming air to 90% of the wet-bulb temperature. The evaporation efficiency remains constant over time.[1]

Fig. 6. Added sprinkler: OJRU

Fig. 7. A 0 to $100^0$C thermometer

If the honeycomb pads used, air cooler efficiency could be increased to 95% depending on air speed. In large commercial and industrial applications honeycomb media is most commonly used [1]. The cost of honeycomb pad is high (around 400 to 600 Rs./sq.ft.) compared to aspen pads ( around 75-125 Rs./pad). Air coolers are mostly used in dry and hot regions as its efficiency is higher when dry bulb temperature of incoming air is higher.

  

Fig. 8. Stationary psychrometer

Fig. 9. Rotating psychrometer

## V. MATHEMATICAL MODEL

Readings were taken on 12.04.2017 and 13.04.2017 in the staff room at Manet, Loni Kalbhor, Pune between 9.00am to 16.30pm. are given in Table:2. Let Tdc -Dry bulb temperature close to fan outlet Td0-Dry bulb temperature outside Tw0- Wet bulb temperature Tw- Water temperature outside ma, mwe, mwh are the mass of air, evaporated water, water circulated in heat exchanger and mass of water respectively. Quantity of water initially filled - 3liters.

Heat removed from air = Heat of evaporation of water + Nozzle heat lost + Heat lost in exchanger

$ma.Ca.\delta T a = mw.Cw.\delta T we + ma.(h1 - h2) +$

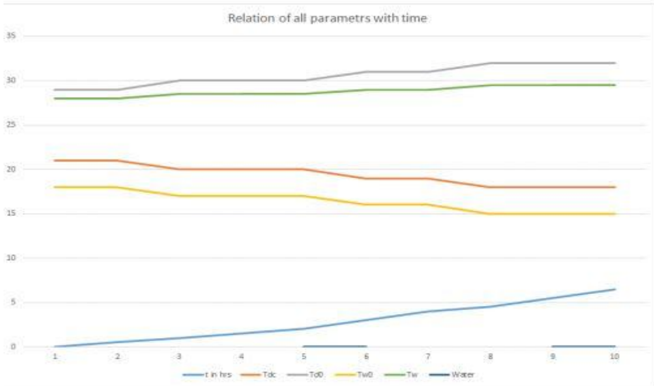


Fig. 10. Time verses Tdc, Td0, Tw0, Twc, Tw

$mwh.Cph.\delta Twh$

$$\delta Ta = \frac{mw.Cw}{ma.Ca} + \frac{mwh.Cwh.\delta Twh}{ma.Ca} + \frac{\delta ha}{Ca}$$

$$Tdc = Tdo - \frac{mw.Cw}{ma.Ca}\delta Twe - \frac{mwh.Cwh.\delta Twh}{ma.Ca} - \frac{\delta ha}{Ca}$$

let, $\frac{mw.Cw}{ma.Ca} = Csh.$

$$\frac{mwh.Cwh}{ma.Ca} = Che$$

$$\frac{1}{Ca} = Cn$$

$$Tdc = Tdo - Csh.(\delta Twe) - Che.(\delta Twh) - Cn.(\delta ha)$$

The above equation could be used to calculate the theoretical values of cooler outlet temperature and tested experimentally. The calculated values for Tdc’ are shown in Table:3 The error is due to fan motor temperature. The cooled air gets heated due to the fan motor and the temperature at the outlet increased. Another reason for the error is initial running of the cooler before taking a first reading. The effective working observed after one hour. It concluded that adding the cooling coil will improve the performance by decreasing humidity (refer fig.14, psychrometry for new process). The constant values are Csh = 3.76, Che = 2 and Cn = 1. So the equation for the cooling system [OJRU] is, T dc = T do − 3.76.(δT we) − 2.(δT wh) − 1.(δha)

Empirical relations

The data plotted as shown in fig.10, 11 and 12. The following relation between ’Tdo’, ’Tdc’ and ’Two’ is obtained.

Tdc = 50-Tdo Tdc=Two-3

The first relation is true only for the temperature range 27 to 33 $^{0}$C. The net (at the outlet near cooler) temperature

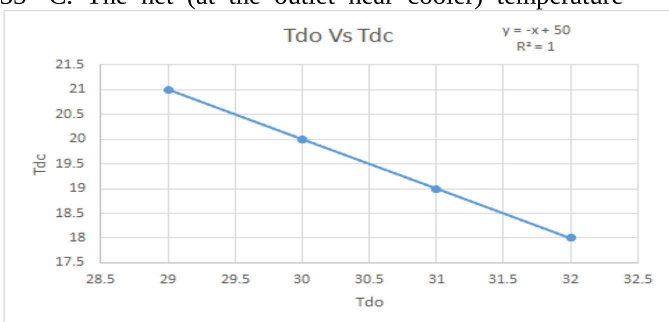


Fig. 11. Tdo verses Tdc

  

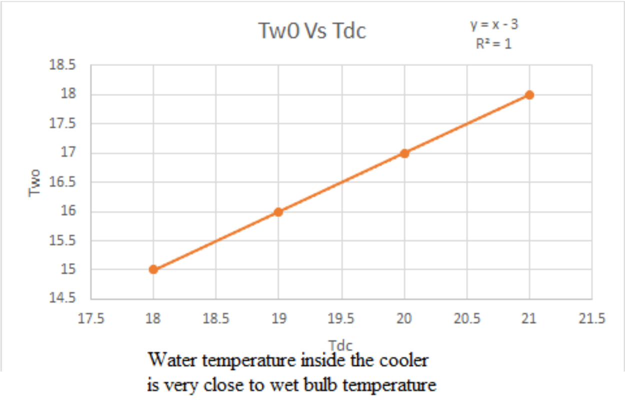


Fig. 12. Tdo verses Two graph

remains constant about 23$^0$C when outside temperature is below 27$^0$C as the rate of evaporation decreases. The net temperature also reaches to constant value about 20$^0$C when outside temperature is above 33$^0$C. In between 27 to 33$^0$C of the outside temperature net temperature varies from 20 to 23$^0$C. The air cooler outlet temperature remains 3$^0$C higher than the wet bulb temperature or water temperature as given by second equation.

## VI. CALCULATION

Pump Specifications: Technical Parameter: Voltage : 165-250V/50 HZ Power : 18 W
H-max : 1.8 m (6 FEET APPROX.)
Output : 1100L/H (@1.8m) Output pipe size:1/2”

Fan specifications:
Rated Voltage :AC 220V, Amp :0.25amp, Frequency : 50-60Hz,
Power :60W,

TABLE II
READINGS FOR TEMPERATURE

| Time | Tdc | Td0 | Tw0 | Tw | Water |
|---|---|---|---|---|---|
| 12.04.2017 | | | | | |
| 9.30am | 21 | 29 | 18 | 28 | - |
| 10.00am | 21 | 29 | 18 | 28 | - |
| 10.30am | 20 | 29 | 17 | 28 | 1.25L add |
| 11.00am | 19 | 29 | 17 | 28 | - |
| 11.30am | 20 | 30.5 | 17 | 28 | - |
| 12.30pm | 20 | 31 | 16 | 28 | 1.25L add |
| 13.30pm | 20 | 31 | 16 | 28 | - |
| 13.04.2017 | | | | | |
| 14.00pm | 18 | 32 | 15 | 29 | - |
| 15.00pm | 18 | 32 | 15 | 29 | 1L add |
| 16.00pm | 18 | 32 | 15 | 29 | 1L add |

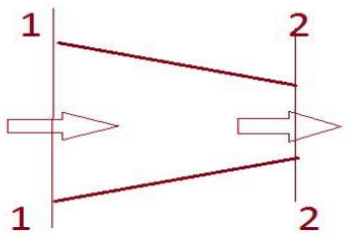


Fig. 13. Nozzle effect due to shape of cooler

Speed :2600 RPM,
Maximum Air Flow :85 CFM
Maximum Air Pressure :6.36mmH2O (Min.5.72mmH2O), Noise :43 dB,
Out Line Dimension : l-170mm x b-170mm x h-51mm , 5 Number of fan blades
The cooling could be achieved by three ways,
Nozzle effect.
Evaporative cooling.
Coil cooling.

Nozzle effect
The nozzle-like structure of the cooler cabinet reduces the temperature by around 1$^0$C. The measurement taken on 13.04.2017 at 12.00 pm without filling water in the air cooler shows the drop in temperature of leaving air up to 1$^0$C. (entering air temperature= 31$^0$C and leaving air temperature = 29.5$^0$C)
Refer fig.13 Area of fan outlet = (3.14)x142 = 154cm2
Air delivery= 84.4CFM = 84.4x0.028 = 2.37m3/min.
Velocity of air at outlet = (2.37x100x100)/154 = 154m/min= 2.56m/s
Using Continuity equation,
The result is practically tested on 13.04.2017 at 12.00pm (pump is off)
Inlet air temperature = 31$^0$C
Outlet air temperature = 30$^0$C

Evaporative cooling
The latent heat of vaporization of water = 22.6x10$^5$ J/kg. Around 1.25 liter water added after 90 min.
So, the total latent heat taken away from water = 31.388kJ/min. The amount of water circulated = 3 kg/min. Heat carried away by air= sensible Heat taken away from water. ma.Cp.δ T = mw.Cw.δ Tw
2.37m3/min x 1.4kg/ m3x1.005kJ/kg K x δT =3 x 4.187 x 2.5 δT = 9.410
Leaving air temperature =29.89-9.41 =20.48$^0$C theoretical
Leaving air temperature = 30-9.41 = 20.59$^0$C
(With actual temp.)
The result is practically tested on 13.04.2017 at 12.00pm (Pump is on)
Inlet air temperature = 31$^0$C
Outlet air temperature = 21$^0$C
Heat exchange
The water is at 18$^0$C after 1hrs. run. So a heat exchanger is added before fan which will exchange the heat between air and water. The heat exchanger is added on 24.05.2017 and tested on 27.04.2017. the results are given in Table: 3.

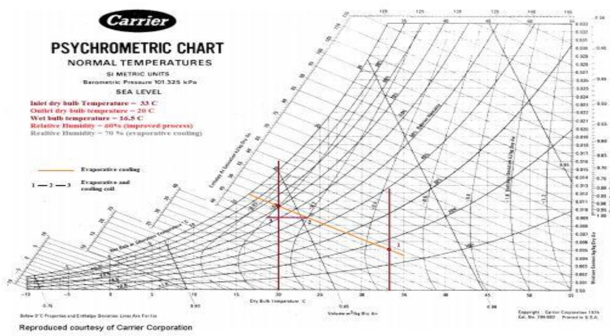


Fig. 14. Psychrometry of new process, Psychrometry chart source- https://lehighcheme.wordpress.com/2013/11/

  

The relative humidity reduces by 10% as shown in fig. 10 psychrometry of new process.

The wet bulb temperature changes.
Heat taken away from air=Heat given to water.
Mass of air x specific heat of air x change in temperature=mass of water x specific heat of water x change in temperature. 2.37m3/min x 1.4kg/ m3x1.005kJ/kg K x δT a = 1.6 kg/min x 4.187kJ/kg K x δT w
(Actual water circulated is 5 kg/min but considering effect of sealing and use of PVC pipes and other parameters like diameter of aluminum pipe etc. the rate of flow of water is taken 1.6kg/min)
3.33 δT a = 6.7 x δT w δT a/δT w = 2.01
If the temperature of water drop by $0.5^0$C, the temperature of air will drop by 10C.
Outlet air temperature = $19.48^0$C (Theoretical) Outlet air temperature = $19.59^0$C (With actual reading)
The readings taken on 26.04.2017 Inlet air temperature = $30^0$C Outlet air temperature =$19.7^0$C

## VII. RESULT AND CFX ANALYSIS

The outlet minimum temperature $19^0$C and relative humidity up to 60 % is possible by using portable OJRU cooler. The test results are given in table below 27.4.2017, [9.00am to 16.30pm] The CFX analysis is done using ANSYS software. The air flow analysis is shown in fig.15. The air is taken in, from the top, side walls but very few air flows from the bottom side. Whereas closing the bottom side, will have a benefit of air circulation over the water surface. Maximum air flow

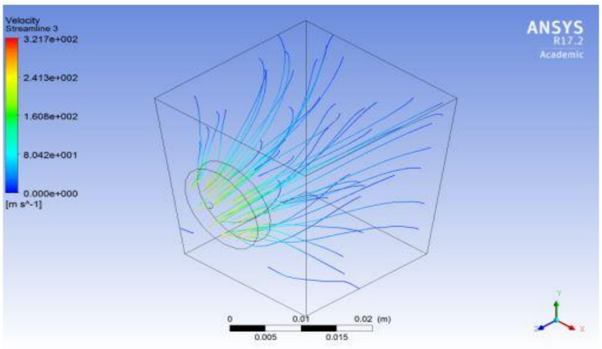


Fig. 15. Air flow analysis

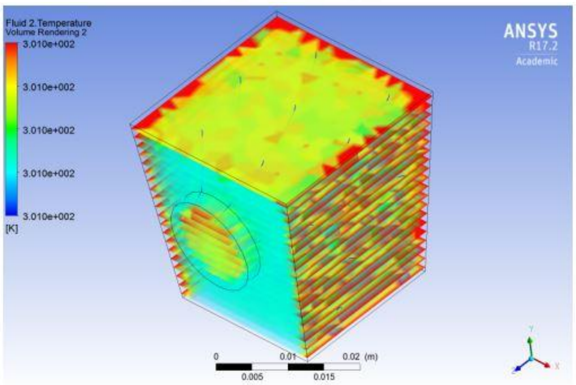


Fig. 16. Flow and temperature variation

occurs from top side as the hot air density is low. The natural circulation advantage is possible. The side holes are required as the air enters from side walls also. The complete analysis of the flow and temperature variation in mixed flow passing through the cooler is as shown in fig.16. The flow of air through the cooler in the room of 10ftx10ft is as shown in fig.17. The air flow from outside to room and from an air cooler

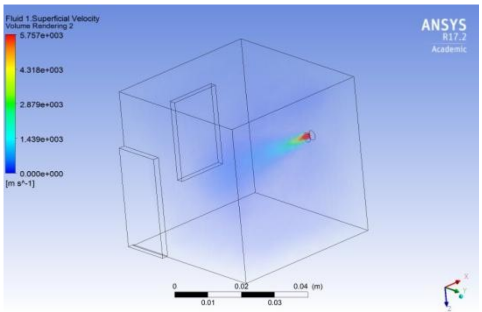


Fig. 17. The flow of air from cooler outlet to room of size 10ft x 10ft

TABLE III READINGS AFTER ADDING ALUMINUM COIL the values of vibration are based on Modified Mercalli Intensity scale. 0.2 to 0.3 vibration on this scale means very weak vibration-instrumental, felt by animals.

| Time | Tdc | Tdc' | error | Tdo | Tw | Twi | Noi | Vibra | Rel. Hum. |
|---|---|---|---|---|---|---|---|---|---|
| 10:15 am | 23 | 20.07 | 2.93 | 30 | 20 | 19.5 | 65DB | 0.2 | 50 % |
| 11:15 am | 22 | 19.16 | 2.84 | 30.5 | 19 | 18.5 | 52DB | 0.3 | 54% |
| 12:15 pm | 20.5 | 17.84 | 2.66 | 32 | 17.5 | 17 | 53DB | 0.3 | 59% |
| 13:15 pm | 21 | 17.37 | 3.63 | 32 | 17 | 16.5 | 50DB | 0.2 | 58 % |
| 14:15 pm | 20 | 17.43 | 2.57 | 33 | 17 | 16.5 | 49DB | 0.2 | 60 % |
| 15:15 pm | 20 | 17.43 | 2.57 | 33 | 17 | 16.5 | 50DB | 0.3 | 60% |
| 16:15 pm | 20 | 17.43 | 2.57 | 33 | 17 | 16.5 | 48DB | 0.3 | 60% |

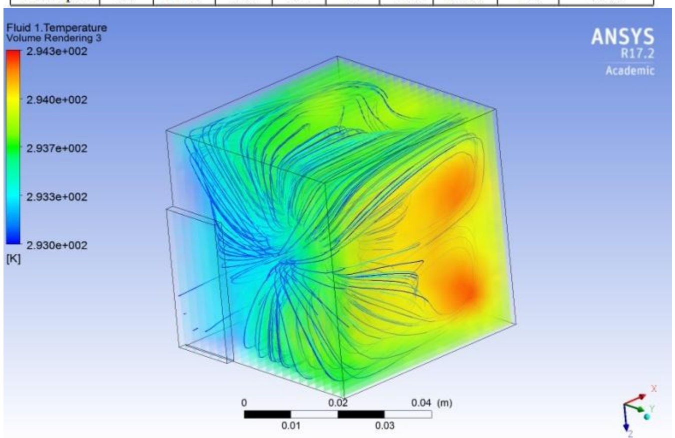


Fig. 18. Cooler outlet air and fresh air flow analysis

to the room is as shown in fig.18. It is possible to cool the same room in 30 min. and bring the room temperature down to $24^0$C. the results were tested and found correct.

## VIII. COMPARISON BETWEEN AIR COOLER AND AIR CONDITIONER

The comparison between air cooler and air conditioner is given in Table 4.

## APPLICATIONS

The portable low-cost air cooler [OJRU] can be used

  

suitably for
Industrial small plants
Small kitchens
Laundries, dry cleaners
Offices
Small shops
Vegetable markets
Workshops

## IX. CONCLUSION

The following are conclusions

A portable air cooler is affordable and suitable for India's climate.

The cooler occupies less space and could be carried to other places with less effort.

The relative humidity level would be brought up to 65% and outlet temperature 20 to $22^0$C which is within comfort zone.

The net dry bulb temperature at outlet of cooler is varying between 20 to $22^0$C depending upon environmental outside temperature.

If the outside atmospheric temperature is high, cooling effect is more as water evaporation rate increases.

A small or large scaled cooler would be made. It is giving the same result. A small unit [AJIANU] as shown in fig. 19 had been tested by the author.

The water temperature is equal to the wet bulb temperature. More and more addition of heat exchanger will bring the air temperature close to the wet bulb temperature below which reduction is not possible.

The outlet temperature of cooler and room temperature addition is $50^0$C within the 26 to $37^0$C range of room temperature.

The fan motor heats the cooled air and increasing the air temperature which would be observed while taking measurements on small scaled cooler [AJIANU]. This could be eliminated by slightly changing the design, which the author will explain in his next paper.

10. Noise is up to 50DB. Silent during operation.
11. The weak vibration of the system makes it most suitable for the domestic and industrial purpose.

Fig. 19. A small scaled unit: AJIANU

TABLE IV
COMPARISON BETWEEN AIR COOLER AND AIR CONDITIONER

| Property | New air cooler | Air cooler | Air conditioner |
|---|---|---|---|
| Initial cost | very low | low | high |
| Installation cost | zero | very low | high |
| Installation time | zero | very less | more |
| Electricity bill | very less | less | more |
| Working fluid | 3 liter water | 6L to 10 L Water | CFC's or $NH_3$ |
| Maintenance | very low | low | more |
| Humidity | 60-65 % | 70-90 % | Controls |
| Temperature | $18\text{-}20^0$ | $19\text{-}20^0$C | control |
| Comfort for | 1-2 persons | 2-5 persons | 5-6 persons |
| Water | 1 L/hr. | 1.5L/hr. | separated |
| Noise | Silent | Noisy | Silent |
| Cleaning | Weekly | monthly | half yearly |

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