Proceedings of the
International Conference on Mechanical Engineering 2005
(ICME2005) 28- 30 December 2005, Dhaka, Bangladesh

ICME05-TH-27

CONSTRUCTION AND TESTING OF AN AIR CONDITIONER CONDENSER WITH CAPILLARY INDUCED COOLING

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ABSTRACT
Novel, less energy utilizing method that can substitute the air-cooled condenser and the fan unit in window type air-conditioners, is presented. The methodology developed here mainly uses latent heat of water to cool the refrigerant. Results of the performance tests on an unmodified window type air-conditioning system and a modified unit are tabulated here. Experiments to determine related characteristics of various types of fabric to select the best possible material for this modification are discussed briefly and the results are revealed. Cotton towelling had the best characteristics for the intended application. The modified unit was tested only with partial success. The knowledge that acquired by this experiment is discussed, to assist further development of this technology and to replace the cooling fan system in window type air-conditioners where applicable.

Keywords: Condenser, Cooling, Capillarity

1. INTRODUCTION
Refrigeration can be defined as the process of removing heat from a substance under controlled conditions [1]. In other words, it is a continued extraction of heat from a matter whose temperature is already below or equal to the temperature of its surroundings. The system extracts heat from a substance and delivers to the external environment. Heat pumps are used for this purpose. Condenser is an integral part of a heat pump. The effectiveness of the condenser will play a major role in the C.O.P of the system. C.O.P refers to the cooling effect derived from refrigeration or an air-conditioner system for a unit input of power [2].

As a result, numerous designs of air conditioner units have been tested and are in use in order to increase the effectiveness of condensers [3]. Low temperature of the liquid refrigerant at the condenser outlet would ensure a high C.O.P of the system. It is possible to reduce both the temperature and the pressure inside the condenser by increasing the effectiveness of the condenser. Hence, it would be possible to reduce the input of energy to the compressor.

Following the developments in this area, the developed air conditioner condenser has adopted a novel technique. It uses fabric to transport water to the condenser using the capillary effect. It forms a thin film of water around the condenser tubes. After absorbing the latent heat from the condenser tubes by the film of water, the water evaporates, cooling the refrigerant inside the condenser.

2. BACKGROUND
Working of a condenser can be described in following three stages. Firstly, the superheated vapor is cooled to its saturation temperature. Secondly, the latent heat of the saturated vapor refrigerant is removed and the refrigerant is condensed. Finally, the temperature of the refrigerant is reduced below the saturation temperature (Sub-cooled) in order to increase the refrigeration effect. The capacity of a condenser is its ability to transfer heat from the hot vapor refrigerant to the condensing medium. The capacity of heat transfer depends on the salient factors discussed below, derived from basic theory of heat transfer and properties of material [4]. Material; since different materials have different coefficients of heat transfer. A high coefficient of heat transfer of a condenser material will lead to smaller sized condensers. In other words, the condensers will be more effective. Amount of contact; the condenser capacity may be altered by controlling the amount of contact between the condenser surface and the condensing medium. This is the reason for incorporating fins on air cooled condenser designs. Temperature difference; the difference of the temperature between the condensing medium and the refrigerant will determine the rate of heat transfer through the condenser. The rate of cooling will be higher when the temperature difference is higher.

According to the condensing medium used, the condensers are classified into the following three groups, namely, air cooled, water cooled and evaporative condensers. Air cooled condensers are generally made of copper or aluminium tubes because of their excellent heat transfer ability. The tubes are usually provided with fins to increase the surface area for effective heat transfer. The fins are usually made of aluminium because of its low weight, good thermal conductivity and low cost. Air-cooled condensers can be classified into two types. Natural convection air-cooled condensers use natural convection to transfer heat from the coil. They require higher surface areas as the rate of cooling is low whereas forced convection air-cooled condensers use fans to blow air to remove heat from the coil. Water-cooled condensers use water as the cooling medium. This method is preferable where an abundant supply of inexpensive water is available. Water-cooled condensers are classified into tube-in-tube condensers and shell and coil condensers depending on the system of flow of water inside the heat exchanger. There is another classification of water cooled condensers according to the way cooling water is being used, namely, wastewater type and re-circulated water type. Wastewater type employs a system where the cooling water, after being used is discharged into a sewer whereas re-circulated type employs a system where the cooling water, after being used is taken through a cycle and cooled in the process and reused. The other type of condenser uses a draft of air and a supply of water to cool water. Most of the heat is removed by evaporation of water. The air also absorbs some sensible heat from water. The water that drops down accumulates in a sump, which is reused.

The discussed method employs evaporative condensing, but uses a novel technique to eliminate the fan unit from the air conditioning system.

3. OBJECTIVE

There were three main objectives to the project. First was to test the performance of an original 24000 Btu/hr (7.01 kW) Westinghouse window type air conditioner. Second was to test different types of fabrics for capillary action to select the best possible fabric for the subsequent modification. Third was to modify the 24000 Btu/hr (7.01 kW) Westinghouse finned air cooled condenser to capillary induced cooling condenser, and test and analyse the performance of the air conditioner with the modified condenser. By doing so, what was ultimately expected was to save energy by eliminating the fan from the condenser unit by means of an innovative technique.

4. THEORETICAL ANALYSIS

Figure 1 below illustrates the advantages of operating a condenser at low pressure. The advantages are reduced compressor work, increase in refrigeration effect and as a consequence increase in the C.O.P. These result in other advantages such as reduction in manufacturing and operating costs, etc.

In an air cooled condenser, sensible heating of air takes place. This means that the specific humidity of air at entry and at exit will be the same. The heat rejected by the refrigerant is absorbed by the air and its enthalpy difference is only due to change in dry bulb temperature. In a capillary induced cooling condenser the heat is first absorbed by the surrounding film of water. This causes the temperature of the water film to rise and evaporate. At steady state, when the water film has acquired a steady temperature, the heat rejected by the refrigerant is absorbed by the condenser cooling air as mass transfer and heat transfer (Figure 2 and 3). This results in an increase in specific humidity as well as dry bulb temperature.

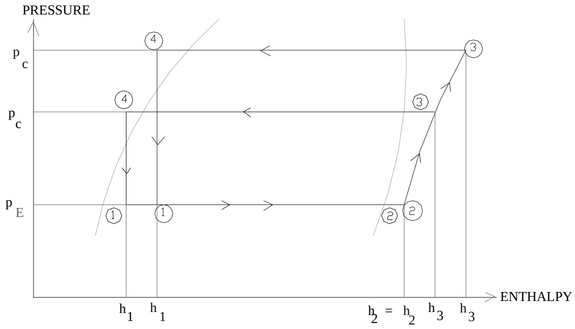

Fig 1. p-h diagram to show advantages of operating at low pressure.

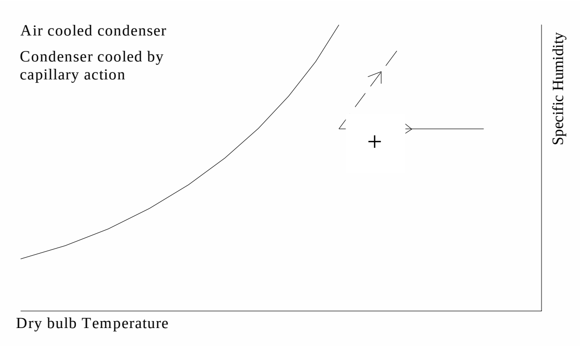

Fig 2. Heat rejection from the condenser by the two methods.

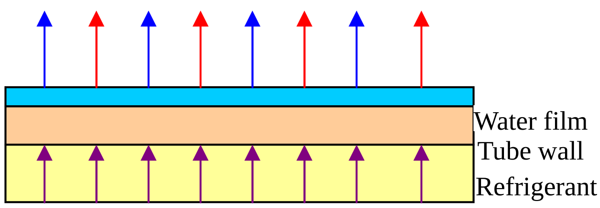

Fig 3. Mode of heat transfer from the refrigerant to the outside environment.

There are two types of airflow through the condenser, which cools the condenser (with the fan unit also in place). They are,

1. Induced vertical flow.

In this type, forced flow is used in blowing away the humidified air transported to the top surface of the condenser by induced vertical flow (Figure 4).

Considering a very small element of the copper tubing such that the temperature of the element can be regarded constant; the analysis of heat transfer is as follows.

Assumptions

1. Temperature of water film around the tube is greater than that of water in the trough. This means that the

increase in humidity is essentially due to evaporation of water at the upper water film than due to evaporation of water in the tray.
2. Length of fibre is small and the time air is in contact with hanging fibre is small.
3. Effect of fibre ignored. Fibre only used in transporting water to the top.
4. Air does not come into contact with air in tray.

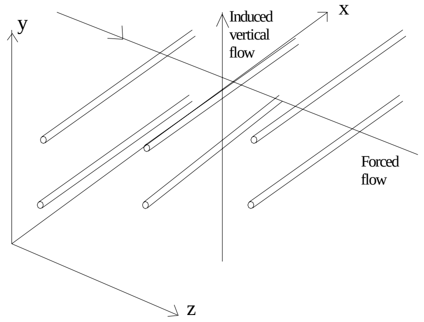

Fig 4. Induced vertical flow

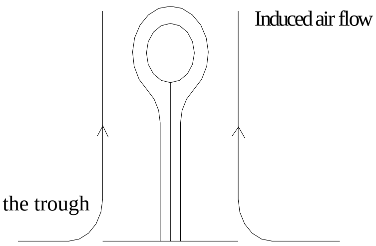

Fig 5. Induced air flow.

Enthalpy increase of induced vertical air flowing over the element	=	Heat gain due to mass transfer	+	Heat gain due to convection

$$\Delta h = 2\pi r\, dx\, [\, h_f (T_s - T\alpha) + h_m (C_s - C_{\alpha})\, h_{fg} \,]$$

$$= \int_{\text{length of tube I}} 2\pi r\, dx\, h_f (T_s - T_{\alpha}) + \int_{\text{length of tube i}} 2\pi r\, dx\, h_m (C_s - C_{\alpha})\, h_{fg}$$

Where,
T_s – Surface temperature of the element
T_a – Ambient temperature
h_f – Local convective heat transfer coefficient
h_{fg} – Latent heat of water
h_m – Local convective mass transfer coefficient
C_s – Saturation water vapour concentration at temperature Ts
C_a – Ambient water vapour concentration
dx – Elemental length
D_h – Total change in enthalpy at the element
$2\pi r$ – Circumference of the tube

The first term of this equation represents the heat transfer from the water film to the air while the second term represents the heat associated with the mass transfer at steady state. The sum of these two terms is equal to the total change in enthalpy of the refrigerant at steady state. At this situation heat and mass transfer occur. By integrating along the tube concerned:

Total increase in enthalpy of air flowing over the i^{th} tube concerned [H_i] $= \int_{\text{Length of } i^{th} \text{ tube}} dh$

Total increase in enthalpy of air flowing over the i^{th} tube concerned [H_i] = Heat rejected by refrigerant flowing through the tube per second

$= m_f\,(h_{ofi} - h_{ifi})$

$$= \int_{\text{Length of tube i}} 2\pi r\, dx\, [\, h_f (T_s - T_{\alpha}) + h_m (C_s - C_{\alpha})\, h_{fg}$$

But, along the length of tube i

i) $T_s = f(x)$ $\quad$ T_{α} = constant

Hence $h_f = G(x)$

ii) $C_s = g(x)$ $\quad$ C_{α} = constant

Hence $h_m = G(x)$

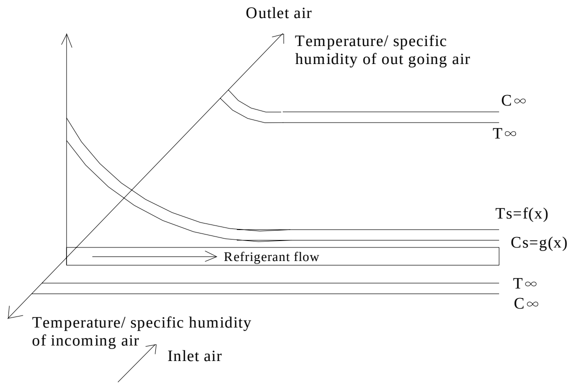

Fig 6. Property variation along tubes.

By evaluating temperature of air passing through the element dx in the ith tube (Figure 6).

Heat rejected by the element $= h_{fx}\, 2\pi r\, dx\, (T_s - T_{\alpha})$

$$= m_{ax}\, (T_{ax} - T_{\alpha})$$

Where,

m_{ax} = mass of air flow over the element dx per integrating

Considering the whole condenser, total increase in enthalpy of air flowing through the whole condenser,
Where,

$$\Delta H = \sum_{i=0}^{N} H_i$$

N = total number of tubes in the condenser

The state of air after heat transfer and mass transfer at the particular place of the tube is different from the state at other points. Hence, if all air was allowed to mix at the outlet, then the state of all air at the outlet can be assigned a particular value or does not vary with position at outlet (Figure 8).

Hence if the change in state of air is represented on a psychrometric chart (Figure 7).

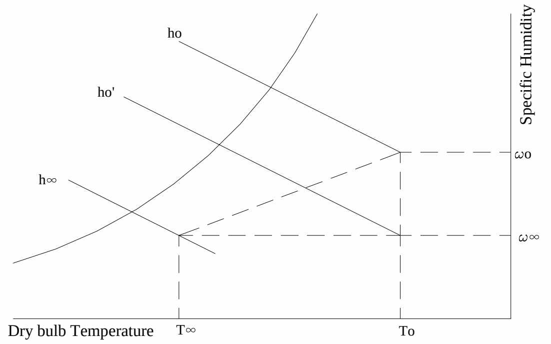

Fig 7. Change of properties

Total enthalpy change = m_a ($h_0 - h_a$)
Where m_a is the total air flow rate through the condenser per second.
Hence m_a ($h_0 - h_a$) = Latent heat gain + Sensible heat gain

$$= m_a [(h_0 - h_0^l) + (h_0^l - h_\alpha)]$$

$$= m_a [h_{fg} (w_0 - w_\alpha) + C_p(T_0 - T_\alpha)]$$

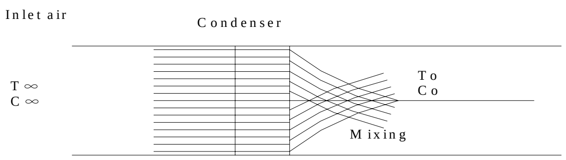

Fig 8. Complete mixing

2. Horizontal forced flow

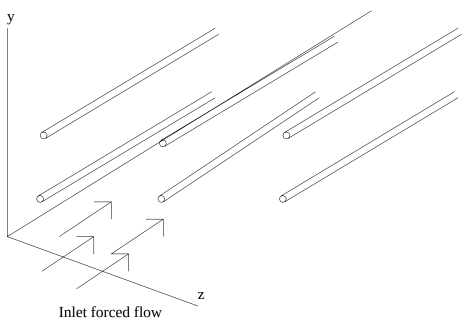

Fig 9. Flow direction

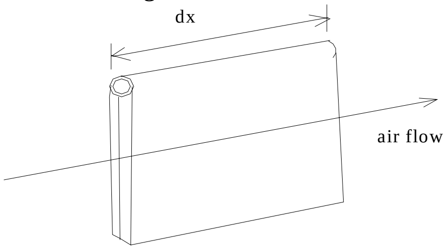

Fig 10. Tube element with fabric

Assumptions

1. Temperature of water film around the tube is greater than water in the tray. This means that the increase in humidity is essentially due to evaporation of water at the upper water film than due to evaporation of water in the tray.
2. Length of fibre is small and the time air is in contact with hanging fibre is small.
3. Effect of fibre ignored. Fibre only used in transporting water to the top.
4. Air does not come into contact with air in trough.

In this case too there is mass and heat transfer.

Increase in enthalpy, dh of air as it flows along the i^{th} tube of length dx

$$= 2pr\, dx [h_f (T_s - T_a) + h_m (C_s - C_a) h_{fg}]$$

Total increase in enthalpy of air flowing over the i^{th} tube concerned [Dh_i]

=x dh i^{th} tube

$$= \int_{\text{length of tube i}} 2\pi r\, dx [h_f (T_s - T_\alpha) + h_m (C_s - C_\alpha) h_{fg}]$$

$$= \int_{\text{length of tube i}} 2\pi r\, dx\, h_f (T_s - T_\alpha) + \int_{\text{length of tube i}} 2\pi r\, dx\, h_m (C_s - C_\alpha) h_{fg}$$

Where,
T_s is temperature at a point x
T_a is ambient air temperature
C_s is the water vapour concentration at a point x
C_a is ambient humidity

Considering the whole condenser, total increase in enthalpy of air flowing through the whole condenser,

$$\Delta H = \sum_{i=0}^{N} \Delta h_i$$

Where,
N = total number of tubes in the condenser

Assuming that the air at the outlet mixes thoroughly enough such that air at every point at a outlet can be assigned the same state,

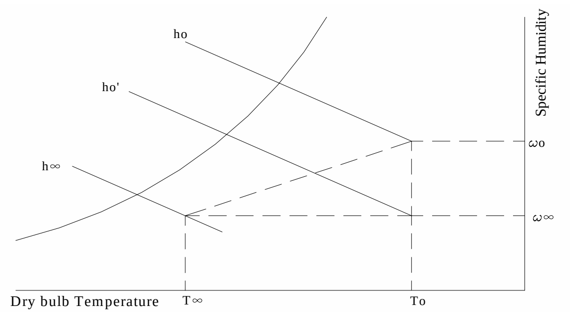

Fig 11. Change of phases

Total heat rejected by refrigerant at the condenser

$$= m_a \, (h_0 - h_i)$$

Where, ma is the total air flow rate through the condenser per second.
h_0 is the enthalpy at the outlet
h_i is the enthalpy at the inlet
Hence,
$m_a \, (h_0 - h_i)$ = Latent heat gain + Sensible heat gain

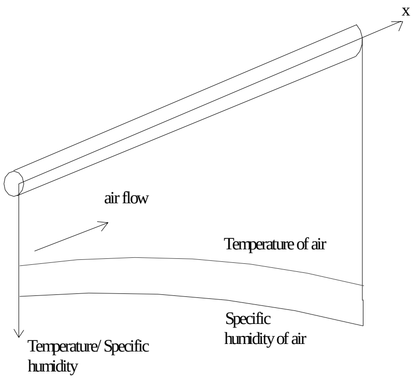

Fig 12. Variation of properties along the tube

5. MODIFICATION

First, the air conditioner system was constructed according to proposal 1 (Figure 13). The reason for choosing proposal 1 was ease of construction. As the time available for the project was limited this configuration was chosen, which needed lesser construction time. The construction procedure is elaborated below. Proposal 2 (Figure 14) needed a higher construction effort.

- Removal of fins of the original condenser
- Mounting the condenser horizontally over a water tray
- Laying of fabric along the condenser tubes in such a way that the fabric ends are partially immersed in the water in the lower water tray
- Use the same blower employed to cool the finned condenser to carry away the moisture
- Fixing pressure and temperature gauges at condenser inlet and outlet

Proposals

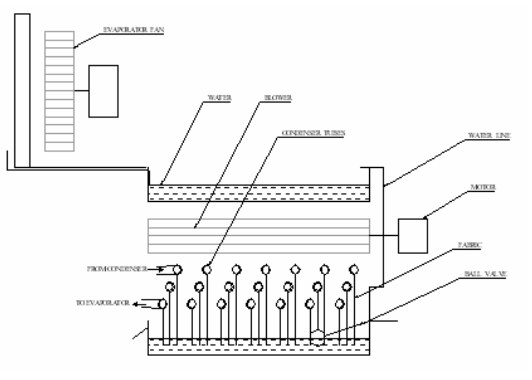

Fig 13. Design option 1 for the modification

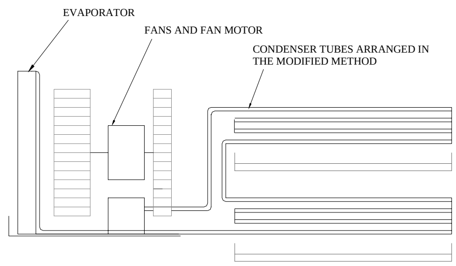

Fig 14. Design option 2 for the modification

As this arrangement too had a lot of shortcomings after construction, the air conditioner condenser unit was modified as shown in Figure 15 below.

The tubes were arranged at an angle so as to collect the liquid refrigerant at the capillary tube end of the condenser. For that the following construction procedure was adopted.

- Removal of "U" tubes
- Rearranging the tubes in two layers and brazing.
- Mounting the two layers of tubing at an angle to the horizontal.
- Connecting the tubes and laying the fabric.

The approximate arrangement of the condenser is shown below (Figure 15). Although there were 48 tubes in all in the condenser, the drawing was simplified by reducing the number of tubes in the drawing.

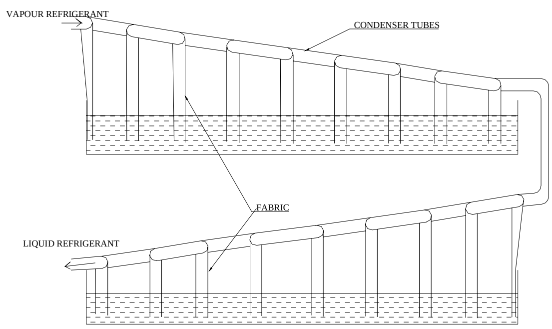

Fig 15. Final configuration

6. RESULTS

The following observations were made by operating the air conditioner with the normal air cooled condenser unit.

Where, power input to the compressor was 2.9 kW and the rate of cooling was 8.7 kW. C.O.P of the air conditioner was found to be approximately 3.03 with the existing conventional condenser with aluminium fins.
the rate of cooling was 8.7 kW. C.O.P of the air

Cool Mode	Condenser Outlet Vel. m/s	Condenser outlet temp ^{0}C	Evaporator outlet Vel. m/s	Evaporator outlet temp ^{0}C
Low	1.92	55.125	6.50	19.3
High	2.057	54.5 C	7.26	19.7

The following observations were made while operating the air conditioner with the modified condenser according to the novel concept. Compressor inlet pressure was 60 Psi, compressor discharge pressure was 450 Psi, condenser inlet temperature was 82 ^{0} C and the condenser outlet temperature was 55 ^{0} C.

7. CONCLUSIONS

The results obtained in this project were encouraging. With a crude design and construction, satisfactory results were obtained. The temperature and pressure of the modified air conditioner system stabilised, but at a higher level than that of the existing widow type air conditioner units. As a result, it could be considered as a project with partial success.

8. DISCUSSION

If the C.O.P of the modified system is greater than that of the original one, then the modified system can be considered successful in terms of efficiency and operating costs. Also, the use of fabric instead of expensive aluminium fins will result in lowering the initial cost, reduced manufacturing time, less complicated manufacturing processes etc. Normally, a finned condenser lasts for about 5 years and after that it has to be replaced. This is due to corrosion of fins. Re-fabricating the removed condenser is also not possible. Throwing away the condensers after such a small period compared with the operating life of other components is not justifiable because of the high unit cost of an air conditioner. A demerit associated with the modified condenser is the necessity for replacement of fabric due to degradation after some time. Use of a synthetic material with necessary characteristics will eliminate this shortcoming. When towelling is compared with employing fins, there is a drastic reduction of cost. As the replacement process of fabric is cheaper and simple, a condenser with capillary induced cooling is suited for any application, where water is freely available. So this condenser can be developed especially for tropical countries such as Sri Lanka.

In the construction process, first, tests were carried out on an existing air conditioner unit. As only a modification to the existing system was done, the same condenser was used, which was in the unit. After fixing the condenser to the rest of the air conditioner unit, the air conditioner was charged with one kilogram of R-22, which was the specified amount to be used in that system. Then the unit was operated. It was found that the pressure drop along the condenser is considerable. The flow rate of the refrigerant inside the condenser tubes was not sufficient, so the suction pressure as well as the discharge pressure of the compressor increased. Fabric was laid and again operated the machine. The reason for the failure of the first attempt might have been the presence of alternate vapour pockets and liquid regions along the length of the tube. For satisfactory operation of a condenser, only a single liquid vapour interface should exist in the condenser and the liquid region should be adjacent to the capillary tubes.

It was possible to establish a single liquid vapour interface, while at the same time facilitating for laying of fabric, by tilting the condenser in such a way that all liquid formed collects at the capillary tube. The modified condenser constructed had two layers of tubing with appropriate slants to facilitate the collection of liquid at the bottom. There can be several reasons for insufficient cooling of the condenser. Tubing of the condenser was closely packed. As a result, fabric could not be laid on each and every tube. If it was done, there would not have been any room for water vapour to escape from the condenser surface. To overcome this problem, a bigger condenser may be employed with tubing, which is apart by an appropriate distance in order to facilitate laying of fabric and for easy removal of heat to the atmosphere. Also, the water at the inside surface of the fabric gets heated due to the heat rejected by the refrigerant, but the water at the outside surface does not get heated.. If the rate of evaporation from the tube surface is greater than the rate of absorbing water from the trough by the fabric, the fabric tends to dry. This shortcoming may also be eliminated by using suitable fabric with more water absorbing qualities and aid capillary action.

When laying the fabric, it was not possible to make the cloth to wrap around the entire condenser tube, resulting exposure of only one half of the condenser tube surface to the film of water. As a result, the process of heat rejection is inhibited. This is a major factor causing the condenser to partially fail in its operation. This can be eliminated by increasing the length of tubing, but it raises another problem. That is, the pressure-drop along the condenser. To counter this, a new compressor to handle that pressure difference could be designed.

Another reason for the condenser to operate unsatisfactorily is the tubing that was used. When the air conditioner was constructed, some tubes got damaged. This might have inhibited flow of refrigerant resulting in high pressures.

If effective cooling of the condenser was observed, elimination of the fan unit might have been possible. The ultimate objective of this project is to eliminate the condenser fan to reduce energy consumption. Further research is carried out at the Department of Mechanical Engineering, University of Moratuwa in relation to suitable fabric and modifications to the air conditioner system where condensed water at the evaporator could also be harnessed in cooling the refrigerant.

9. ACKNOWLEDGEMENT

Prof. P.A. De Silva who came up with this ingenious idea has to be commended. The project group is indebted for his contributions throughout the project.

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