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Research paper

Comparison of heat transfer coefficient for different fabrics by vapor-compression system

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Abstract

The selection of a suitable fabric layer is an important aspect in the development of a cooling garment. One of the essential ingredients in selecting fabric for cooling garments is high heat transfer coefficient. In this study five different type of knitting fabrics with similar woven pattern were selected. The fabrics were attached to a vapor-compression system which is one of the most important systems in cooling garments. Heat transfer coefficient was calculated for each fabric for three different refrigerator flow rates. The most efficient fabric for applying in cooling garments was determined from the point of heat transfer coefficient.

Keywords: *Cooling Garment; Vapor-Compression System; Heat Transfer Coefficient; Knitting Fabric; Refrigerant Mass Flow Rate.*

1. Introduction

High temperature and humidity in the work place have been of a major concern to diverse industries. In this situation, several detrimental effects occur, such as dehydration, heat stress/stork, elevated heart rate and etc. In this situation, person must be cooled to prevent the physical damage and increase the efficiency [1], [2]. Therefore, came into being need for cooling systems that body temperature can be placed in appropriate circumstances in different industries such as military, steel mills, Manufacture of glass and crystal, mining and service jobs such as firemen and athletes [3].
Cooling garments can be divided into two types, passive and active [4]. The passive cooling garments are like ice or frozen gel packs. In this type of cooling garments an external power source to operate the system is not require and continually these garments should charge with frozen ice or gel packs. In active cooling garments, heat will be away from the body with fluids (air, water, solution, and …). These systems used mechanical devices to move the fluid like pump, fan and etc.
Cooling garments with vapor-compression system are one of the most important active cooling garments. In these garments, refrigeration passes through a tube which is placed in a garment by a compressor and then heat of body transferred to the refrigeration [5]. Each type of cooling systems has advantages and disadvantages but all cooling garments must have several properties such as top portability, steady and high strength, low weight, high quality, and no harm to human body.
Research on various models of cooling garments shows that the temperature of the cooling garment should be close to the skin temperature. The temperature must be low enough to enable the heat transfer from the body, but not too low which cause users to feel uncomfortable. Research has been done to determine the average comfortable skin temperature. Nuunely [6] showed that for individuals at rest, this temperature is approximately 33˚c.The desired temperature to feel comfortable declines as the activity level of people increases.
Epstein [7] analyzed several fluids for cooling such as air, water and ice. He explained two methods for describing the performance of a cooling suit, the efficiency and the effectiveness. The efficiency is the amount of cooling per unit area, or heat flux, and the effectiveness is the total cooling of a particular area of the body. Their results showed that cooling of the torso is more effective than other parts of the body due to the larger surface area. The head was shown to be the most efficient area to cool. However, due to the limited area, it is a less effective area to cool. One drawback of using cooling vests with incorporated tubing according to Epstein is that sweat rate increased due to damp environment.
Pourmohamadian [8] conducted research on a thin, flexible, non-metallic heat exchanger that could provide an alternative to the standard tubing currently used for cooling garments. The micro-channel heat exchangers were made from a heat sealable polyimide film and had a thickness of 0.2 mm. These heat exchangers were very thin and flexible therefore do not have significant mass and can handle pressures up to 2.07 MPa (300 psi). The fact that they are thin and flexible means they would lend themselves well to being used as heat exchangers for a cooling garment. They are also capable of withstanding the pressures associated with a vapor compression refrigeration cycle using R-134a, which means that the refrigerant could be directly routed to the cooling garment without the need for an additional closed water loop. The flexible heat exchangers are also compatible with refrigerant R-134a.
Most of the cooling garment researches focused on the effectiveness of cooling in different parts of body [9], intermittent and regional cooling [10], tubing pattern, liquid flow rate in tubing, liquid inlet temperature, efficiency of whole garment, and others [6]. The fabrics used in the cooling garments have not been investigated much before. Cotton fabrics are still dominant for cooling garments application.

In the initial models for cooling garments, many of them were constructed with tubing sewn to one fabric layer such that the tubing rests directly on the skin. However, a two-layer system with the tubing sandwiched between two fabric layers has more wearer comfort. An inner fabric layer, as one of the important part of a cooling garment, with high thermal conductivity can enhance the heat exchange between body and the cooling liquid and improve the efficiency of the system [11].

During the past two decades, new fabrics have been engineered and produced. Then, heat transfer coefficient has been calculated for various fibers and fabrics [12]. However, the heat transfer coefficient of fabrics calculated by vapor-compression system can be a good simulation for determines this parameter for each fabrics.

Energy from hot fluid to cold fluid transferred in three ways: conduction, radiation, and convection. In conduction, heat reduced through physical contact, For example placing an ice pack on the body.

The basic heat transfer equation for conduction is:

$$G = \frac{Q}{t} = \frac{KA(T_H - T_C)}{d} \quad (1)$$

Where A- area of the human body ($A = 2m^2$), K- thermal conductivity of the air surrounding the body ($K = 5.7 \times 10^{-5} \frac{w}{cm.°C}$), T_H, T_C- (°C) temperatures of hot and cold area, respectively and d – distance between skin and surrounded surface [13].

2. Experimental

2.1. Materials and devices

In this experiment, first, a vapor- compression system was constructed with listed devices:

1) Compressor with a power of 1/8 hp
2) Copper capillary tube with a diameter of 0.31mm and a length of 3 m
3) Accumulator
4) Refrigerant R-134a
5) Copper U-shape Evaporator
6) Air- cooled condenser.
7) Filter - dryer for refrigerant R-134a.
8) Flow meter type KT800-6F manufactured by Fisher- co.

Five fabrics were used in this study and their fiber contents, fabric structures, and thicknesses are listed in Table 1. Fabric thicknesses were measured (for each fabric, ten thickness were measured and the average are listed in Table 1) using a thickness gage according to ASTM D1777-64.

Table 1: Fabrics Tested in this Study

Fabric no	Fiber content	Fabric structure	Thickness(mm)
1	Polyester	Knit (Milano)	0.72
2	Nylon	Knit (Milano)	0.53
3	Acrylic	Knit (Milano)	0.97
4	Cotton	Knit (Milano)	0.71
5	Polypropylene	Knit (Milano)	0.89

2.2. Vapor-compression system and manufactured testing machine

A schematic view of the vapor-compression system which was manufactured to determine the heat transfer coefficient of fabrics is shown in Fig.1.

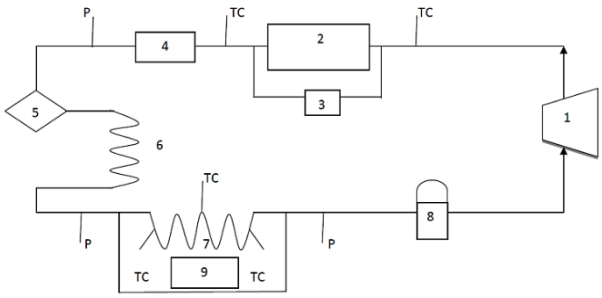


Fig. 1: Schematic View of the Vapor-Compression System: 1- Compressor 2- Condenser 3- Fan 4- Flow Meter 5- Filter – Dryer 6- Capillary Tube 7- Fabric 8- Accumulator 9- Hitter, P- Manometer and TC- Thermocouple.

The U-shaped tube, which was placed within the fabrics, was played the role of evaporator in a vapor-compression system. The tube was made from copper. Its outer diameter was 6 mm and inner diameter was 4 mm. length of tube was 170 cm. Thermocouples were located in three parts: beginning, middle, and end of the tube to measure temperature. After reaching a steady state system, the following data were recorded:

1) Refrigerant mass flow rate
2) Inlet and outlet temperatures of the condenser
3) Outlet pressure of the condenser
4) Inlet and outlet pressure of the evaporator
5) The temperature at the inlet, outlet, and center of the evaporator.

2.3. Calculating heat transfer coefficient

In this study, boiling heat transfer coefficients of R-134a were obtained by using five different types of fabric (polyester, nylon, acrylic, cotton, and polypropylene) at five temperatures 20, 30, 40, 50, and 55 °C in three different mass flow rate of refrigerant (98.65, 147.18, 197.29 ($\frac{kg}{m^2s}$)). Copper tube used as a blank sample. Calculation steps are as follows:

1) First, Refrigerant mass flow rate was calculated by equation (2):

$$\rho_2 \times \dot{m} = q_2 \quad (2)$$

Where $\dot{m}$- Refrigerant mass flow rate, q_2- R-134a refrigerant mass flow rate, and ρ_2- Density of the refrigerant R-134a.

2) The temperature of the evaporator (Q_{eva}), calculated by equation (3):

$$Q_{eva} = \dot{m}(h_2 - h_1) \quad (3)$$

Where $h_2 - h_1$- difference between exhaust gas enthalpy and inlet fluid enthalpy in the evaporator. A schematic view of flow of inlet and outlet in the evaporator is shown in Fig.2.

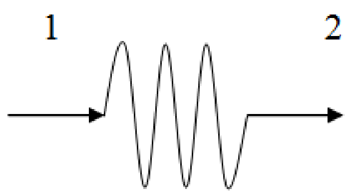


Fig. 2: Schematic View of the Evaporator

3) Radial heat flux to the evaporator (q'), calculated by equation (4):

$$q' = \frac{Q_{eva}}{A_i} \quad (4)$$

Where A_i- Inner surface of the tube which was used as evaporator, calculated by equation (5):

4) Temperature drop across the tube wall (Δt_w), calculated by equation (5):

$$\Delta t_w = \frac{q' \, d_i \, \ln(\frac{d_0}{d_i})}{2K_w} \quad (5)$$

Where q´- Radial heat flux, d_i- Internal diameter of the tube, d_0- Outer diameter of the tube, k_w- Thermal conductivity (Thermal conductivity for a copper tube is 401($\frac{kw}{mK^{\circ}}$).)

5) Average temperature of the external wall of the evaporator (t_{wal}), calculated by equation (6):

$$t_{wal} = \frac{\sum_1^3 t_{ws}}{3} \quad (6)$$

6) Average temperature of the inner wall of the evaporator (t_{wi}), calculated by equation (7):

$$t_{wi} = t_{wal} - \Delta t_w \quad (7)$$

7) 7- Finally, Evaporator heat transfer coefficient (h), calculated by equation (8):

$$h = \frac{q'}{(-t_s + t_{wi})} \quad (8)$$

Where t_s-saturation temperature.

Moreover, the effect of various factors on heat transfer coefficients has been carried out such as refrigerant mass velocity. To study the effects of refrigerant flow rate, experiments were done in three different refrigerant mass flow rates. For determining the most appropriate fabric, percentage decrease of heat transfer coefficient of each fabric was calculated by equation (9):

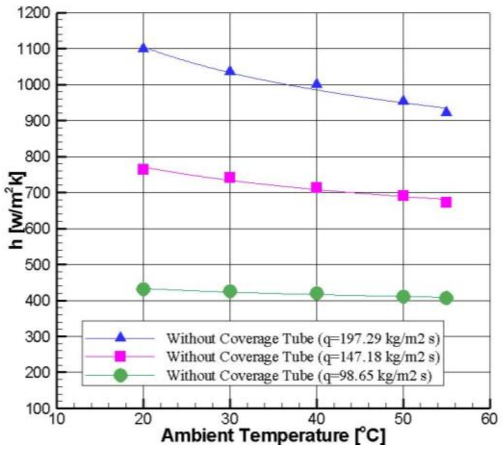
$$\text{Percent decrease} = \frac{h_{max} - h_{min}}{h_{max}} \times 100 \quad (9)$$

Where h –Average of heat transfer coefficient of each fabric.

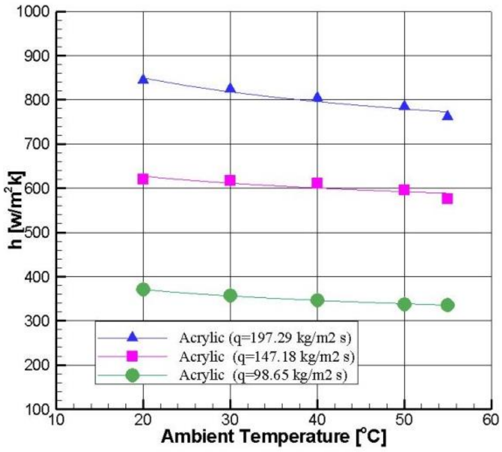
3. Results and discussion

Fabrics must have high heat transfer coefficient to become suitable for application in cooling garments with high efficiency.
The behavior of heat transfer coefficient versus temperature was shown in the following graphs. The heat transfer coefficient of a fabric which is closer to the heat transfer coefficient of the copper tube is much desirable because it exhibit more efficient heat transfer from body to outside. If other parameters remain constant, with increase in refrigerant mass flow rate boiling heat transfer coefficient will increases. In fact, higher refrigerant mass flow rate leads to more turbulence in the boiling layer of liquid and therefore boiling heat transfer rate will increased.

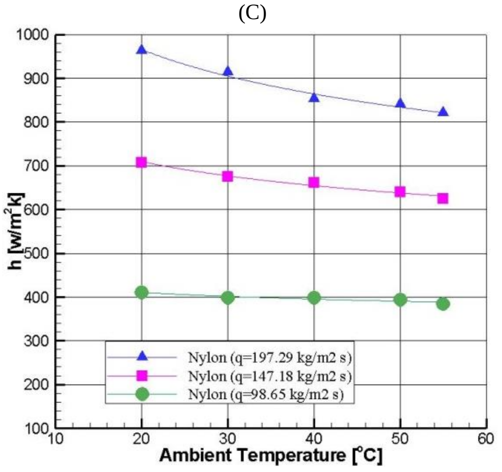
(A)



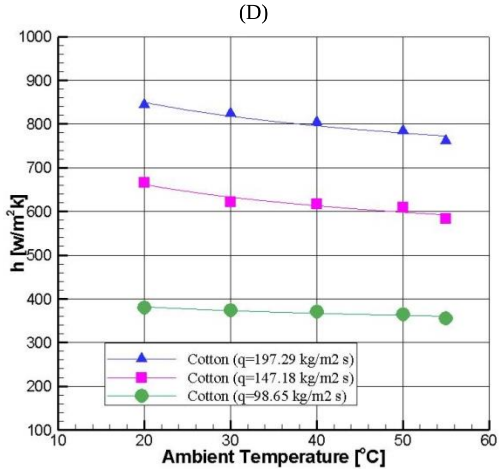
(B)



(C)



(D)



(E)

(F)

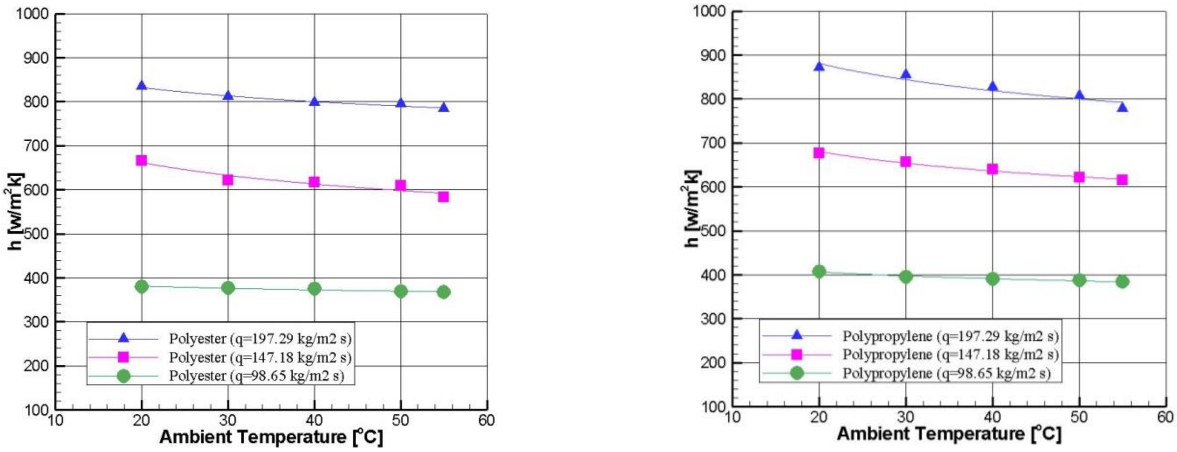


Fig. 3: Changes of Heat Transfer Coefficient Vs. Temperature of Three Different Flow Rate of Refrigerant for A: Copper Tube. B: Acrylic. C: Nylon. D: Cotton. E: Polyester. F: Polypropylene.

In Fig.3 all graphs show decrease in heat transfer coefficient with temperature. The slope of curves increases with increasing flow rate of refrigerant. This happened due to temperature difference of saturation state and wall decreases with increasing temperature. Therefore, refrigerant need to absorb less heat to evaporate and heat transfer coefficient will reduce. In addition, type of fabric affects heat transfer coefficient and percentage changes. Percentage of change in mass flow ratio is shown in table 2.

Table 2: Percentage Change of Maximum Mass Flow Ratio to Minimum Mass Flow Ratio

Fabric Type	Percentage change
copper tube	58.2%
acrylic	42%
nylon	54.75%
cotton	54.03%
polyester	53.52%
Polypropylene	52.5%

According to Table 2, minimum and maximum of heat transfer coefficient of tube is for the one which is covered with polyester and nylon, respectively. It is obvious that change of heat transfer coefficient in copper tube is higher than all fabrics.

Results show that nylon and acrylic have the highest and lowest heat transfer coefficient in all circumstances, respectively. Nylon is the best candidate for utilizing in the field of cooling garments.

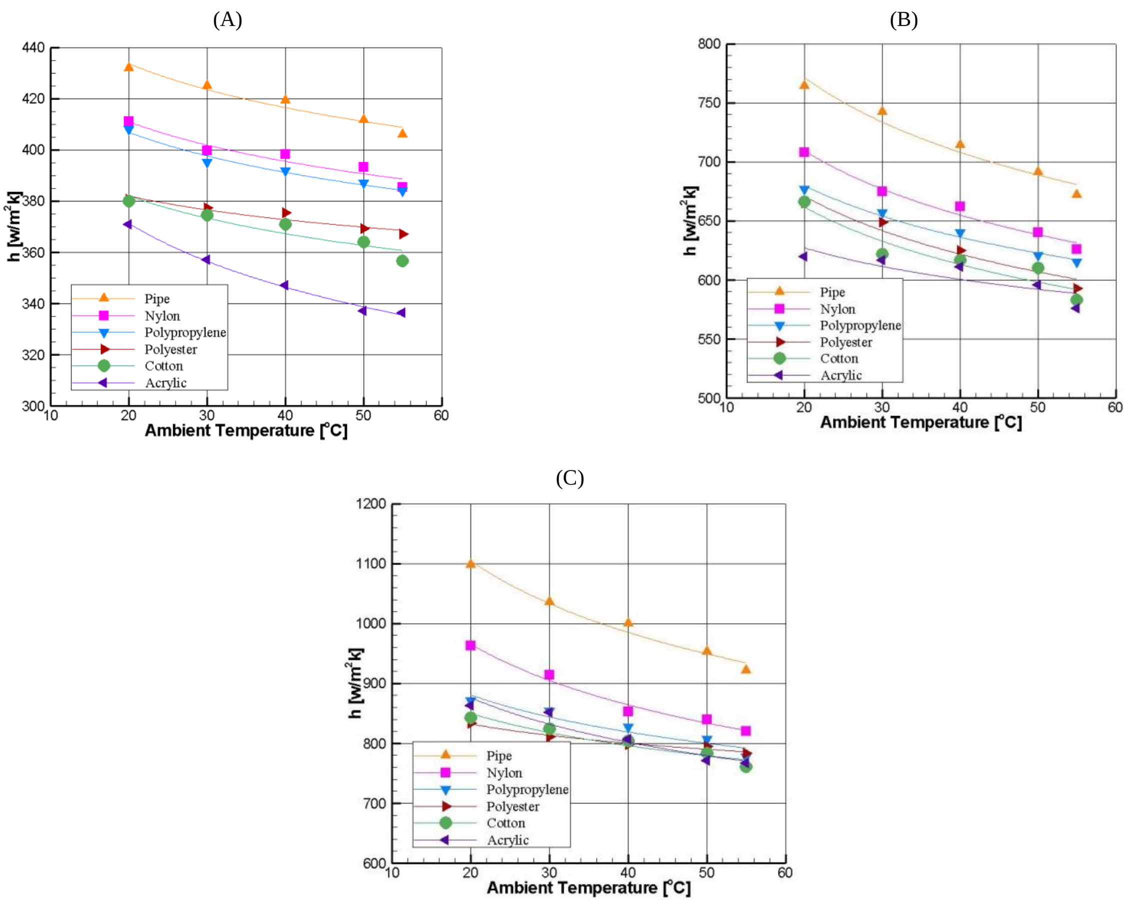


Fig. 4: Heat Transfer Coefficient of Fabrics in Three Flow Rate of Refrigerant A: $(98.65\frac{Kg}{M^2S})$, B: $(147.18\frac{Kg}{M^2S})$, C: $(197.29\frac{Kg}{M^2S})$

Percent decrease for each fabrics compare to copper tube in three different refrigerant mass flow rates, are shown in Table 3.

Table 3: Percent Decrease of Heat Transfer Coefficient for Fabrics Compare To Copper Tube in Three Different Refrigerant Mass Flow Rates

Fabric type	Refrigerant mass flow rate $\frac{kg}{m^2 s}$		
	98.65	147.18	197.29
Acrylic	16.5%	15.63%	19%
nylon	5.1%	7.53%	12.3%
Cotton	11.1%	13.46%	19.8%
polyester	10.7%	12.22%	19.3%
Polypropylene	6.1%	10.34%	17.36%

4. Conclusions

One of the major challenges in work places is heat discomfort. In this situation cooling garments are required to help the process of human body cooling [14]. A body cooling garment which utilizes fluid-carrying tubes and provides both air and vapor permeability to make a flexible, comfortable garment is one of the efficient one. Types of fabrics and fibers which are used in cooling apparel play a key role in transferring heat, moisture management and comfort ability.

In this research, different experiments were performed to determine the most effective fabric from the point of heat transfer coefficient for utilizing in cooling apparel. Results showed nylon will have better performance compare to other fibers for process of human body cooling.

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