Thermal Comfort Control for Residential Heat Pump

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Abstract

The improvement of themal comfort has been one of the concerns with the increase of heat pump air conditioners for residential use. Thermal comfort of conventional air conditioners for residential use are controlled by means of air temperature as thermal environmental factors. However, it is a well known fact that man's thermal sensation is influenced not only by air temperature but also by air velocity, radiation and humidity. Therefore, in order to improve thermal comfort, the residential air conditioner should be controlled by the data based on the above thermal environmental factors.

In the viewpoint of improving thermal comfort, we have developed the sensors which can measure the thermal environmental factors and the residential air conditioner controlled by the data calculated from these factors. This paper presents the construction of the sensors and some experimental results when the residential air conditioner is controlled by using these sensors. Besides a normal temperature sensor, a radiation sensor, a velocity sensor and a humidity sensor are mounted in a remote control kit. Each sensor can individually measure air temperature, radiant temperature, air velocity and humidity. Thermal environmental signals are transmitted to the main controller of the air conditioner.

We have also developed microcomputer programs which enable the following controls.

1) SET* (Standard New Effective Temperature) known as the superior thermal index at present is calculated from measured data.
2) Rotating speed of the inverter driven rotary compressor is controlled according to the difference between the calculates SET* and the desired SET*.
3) The air discharge direction is automatically adjusted so as to make the air velocity around man less than 0.4 m/s.

By the experimental test of our newly developed air conditioner, we have obtained the following results.

1) Thermal comfort can be obtained equally in spite of the variation of the thermal environmental factors.
2) Thermal discomfort occurred by the excessive air flow can be diminished.

CONTROLE DU CONFORT THERMIQUE POUR LES POMPES A CHALEUR ET LOCAUX RESIDENTIELS.

RESUME : L'amélioration du confort thermiquc est l'une des préoccupations entraînées par l'augmentation dcs conditionneurs d'air de locaux résidentiels à pompe à chaleur. Le confort thermique des conditionneurs d'air habituels pour locaux résidentiels est régulé à l'aide de la température de l'air comme facteur d'environnement thermique. Cependant, il est bien connu que la sensation thermique humaine dépend non seulement de la température de l'air mais aussi

de la vitesse de l'air, du rayonnement et de l'humidité. Pour améliorer le confort thermique, le conditionneur d'air pour locaux résidentiels doit donc être contrôlé par des grandeurs relatives aux facteurs ambiants ci-dessus.

Pour améliorer le confort thermique, les auteurs ont mis au point des détecteurs pouvant mesurer les facteurs de l'environnement thermique et le conditionneur d'air pour locaux résidentiels est régulé par les valeurs calculées à partir de ces facteurs. Ce rapport présente la construction des détecteurs et quelques résultats expérimentaux lorsque le conditionneur d'air pour locaux résidentiels est régulé au moyen de ces détecteurs. En plus d'un détecteur normal de température, un détecteur de rayonnement, un détecteur de vitesse et un détecteur d'humidité sont montés dans un ensemble de régulation à distance. Chaque détecteur peut mesurer individuellement la température de l'air, la température radiante, la vitesse de l'air et l'humidité. Les signaux de l'environnement thermique sont transmis au dispositif de régulation principal du conditionneur d'air.

Les auteurs ont mis au point également des programmes de micro-ordinateur permettant les régulations suivantes :

1. Le SET* (nouvelle température effective normale) connu comme indice thermique supérieur actuel est calculé d'après les valeurs mesurées.
2. La vitesse de rotation du compresseur rotatif entraîné par inverseur est régulée suivant la différence entre le SET* calculé et le SET* désiré.
3. Le sens du refoulement d'air est ajusté automatiquement de façon à ce que la vitesse de l'air autour des sujets soit inférieure à 0,4 m/s.

Avec l'essai expérimental du conditionneur d'air nouvellement mis au point, les auteurs ont obtenu les résultats suivants :

1. Le confort thermique peut être obtenu également malgré la variation des facteurs d'environnement thermique.
2. L'inconfort thermique dû à un écoulement d'air excessif peut être réduit.

THERMAL COMFORT CONTROL FOR RESIDENTIAL HEAT PUMP

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1. INTRODUCTION

The improvement of thermal comfort has been one of the concerns with increase of the application of heat pump air conditioner for residential use.
In recent years, inverter driven heat pumps are widely used in the field of air conditioners in Japan because of the energy saving and improvement of thermal comfort due to the linear capacity control of the compressor. But, most of these air conditioners are controlled only by room air temperature as thermal environmental factors. However, it is a well known fact that thermal comfort is influenced not only by air temperature but also by other thermal environmental factors such as air velocity, radiation and humidity. So, thermal comfort is not well controlled in spite of the use of the inverter driven compressor.

In the view point of taking account these thermal environmental factors into consideration as control signals, we have developed the sensors which can measure the above environmental factors and the control methods based on the data obtained from these sensors. Also, in order to improve thermal comfort, we have developed the directional control of discharge air flow for the purpose of excluding draft to the occupants caused by the excessive air flow.

In this paper, we will introduce the newly developed sensors with which thermal comfort index based on the SET* (Standard New Effective Temperature) can be obtained. The control system using these sensors are also developed which leads the improvement of thermal comfort. Some experimental results are obtained by the real operation of the heat pump room air conditioner in which these sensors and control systems are applied.

2. DESCRIPTION OF THE CONTROL SYSTEM

The residential inverter heat pump air conditioner which we developed consists of an indoor unit, an outdoor unit and a remote controller.
Each component has a micro-computer based control unit which controls the rotating speed of the indoor and outdoor fans and the compressor.
Fig.1 shows a block diagram of the control system for this air conditioner.
The work of these control units are described below.

2.1 Indoor control unit

The indoor control unit controls the whole system by receiving the data transmitted from the remote control unit and by commanding the outdoor control unit through the serial data communication. The main works of the indoor control unit are as follows.

(1) changes mode of operations according to the signal data transmitted from the remote control unit.

I.I.F - I.I.R - Commissions B1, B2, E1, E2, - Purdue (U.S.A) - 1988

(2) adjusts the frequency of the compressor by commanding the outdoor control unit. The frequency of the compressor is determined according to the difference between the preset SET* and the calculated SET* based on the thermal environmental factors.
(3) varies the rotating speed of the indoor fan according to the indoor heat exchanger temperature.
(4) adjusts the air discharge direction so as to prevent the non-heated air from direct bodily contact.

2.2 Outdoor control unit

The outdoor control unit is equipped with the inverter circuit in order to vary the frequency of the compressor. The main works of the outdoor control unit are as follows.

(1) adjusts the rotating speed of the compressor according to the command of the indoor control unit.
(2) controls the defrosting operation in heating based on the outdoor heat exchanger temperature.
(3) turns on and off the four way valve according to the mode of operations.

2.3 Remote control unit

The remote controller is equipped with a room air thermistor, a radiation sensor, a velocity sensor and a humidity sensor in order to monitor the four thermal environmental factors. The data obtained from the four thermal environmental sensors are transmitted to the indoor control unit.

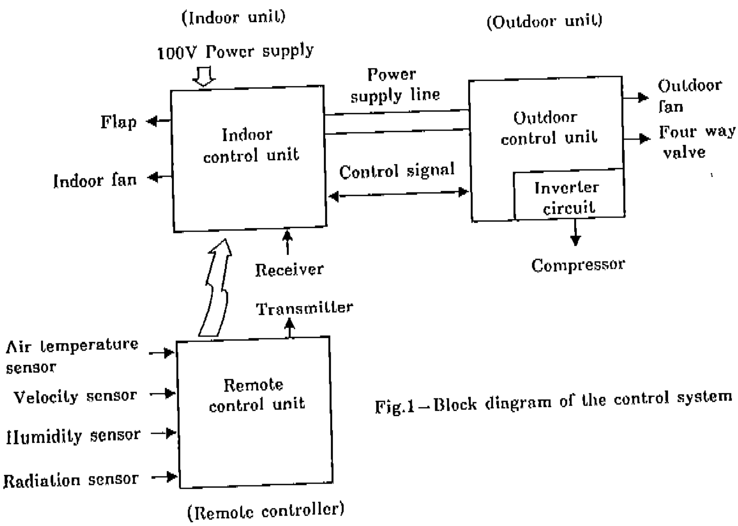


Fig.1 – Block diagram of the control system

3. DESCRIPTION OF THE SENSORS

In this section, the structures of the radiation sensor, the air velocity sensor and the sensing methods which are developed in this work are discussed.

3.1 Radiation sensor

Fig.2 shows the configuration of the radiation sensor in the remote controller. The radiation sensor is in the form of a normal thermistor insulated with the polyethylene foam on the inside surface of the remote controller.

This sensor monitors the influence of the radiational heat transfer between the surrounding walls of the room and the outside surface of the remote controller, sensing the mean radiant temperature throughout the operation.
Fig.3 shows the comparison of the difference of the influence between the theoretical and experimental mean radiant temperatures.
Theoretical temperature and experimental temperature show good agreement.

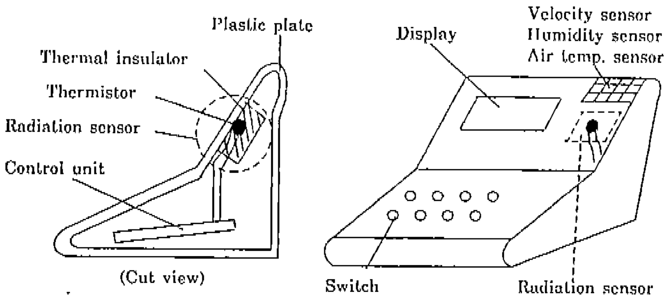


Fig.2—Configurations of radiation sensor and remote controller

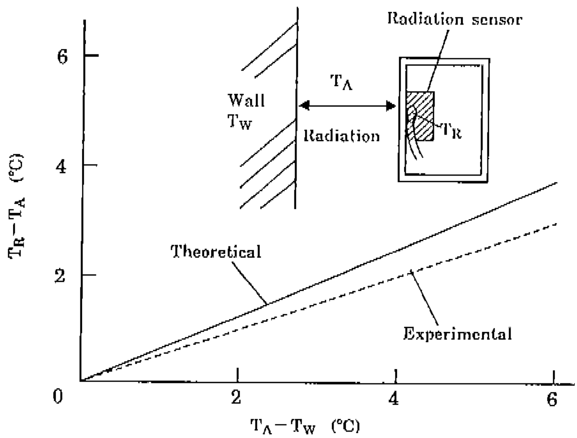


Fig.3—Comparison of experimental and theoretical results

3.2 Air velocity sensor

The air velocity sensor monitors the air flow rate around the remote controller where man is assumed to be. A self heating thermistor is used as the air velocity sensor. The temperature of this thermistor rises as electrical power is supplied.
The temperature rising is influenced by the air flow rate around the thermistor due to the heat radiation.
Fig.4 shows the principle of the air flow sensing and the electrical circuit schematically. The principle of the air flow sensing is described below.

(1) first, SW1 is turned on and the electrical power is charged in the condenser C until the voltage reaches E_1(V). If the voltage reaches E_1(V), SW1 is turned off.
(2) second, SW2 is turned on and the electrical power is supplied to the self heating thermistor. Consuming the power in this thermistor, the voltage of the condenser C is gradually decreased. If the voltage reaches E_2(V), SW2 is turned off.

(3) in the discharging process of the condenser C, the time T decreasing from E_1(V) to E_2(V) is different by the air flow rate. Therefore, the air flow rate is obtained by measuring the time T.

The time T depend on the air temperature around the thermistor, so the air flow rate is corrected with the air temperature.

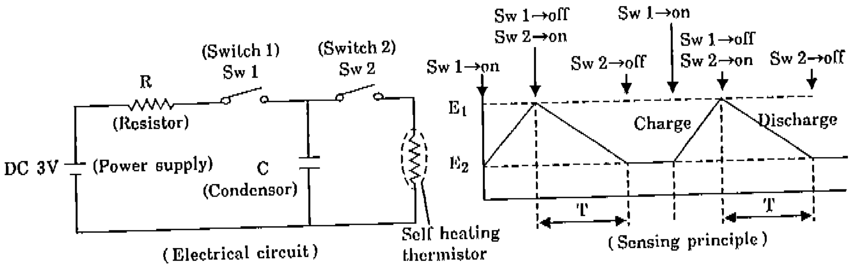


Fig.4 – Schematic diagram of electrical circuit and sensing principle in velocity sensor

4. EXPERIMENTAL RESULTS

4.1 Comfort control by SET*

Most of the conventional inverter air conditioners have been controlled so as to make the room air temperature reach to the preset temperature by varying the rotating speed of the compressor. However, in this conventional thermal control, the thermal comfort is not always satisfactory. Because, thermal sensation is influenced not only by air temperature but also by other thermal environmental factors such as air velocity, radiation and humidity.

Various thermal comfort indices considering these factors have been proposed /1 //2 //3 /. Among these, the SET* is said to be the superior thermal comfort index. We have developed the control based on the SET* with which the equal thermal sensation can be obtained in the various thermal environment.

Fig.5 and Fig.6 show the influence of radiation and air velocity respectively calculated by the SET* theory for thermal sensation. When the air velocity reaches 1.0m/s, thermal sensation is equivalent to approximately 4°C decrease in the room air temperature. Also, the degree of thermal sensation influenced by radiation varies linear according to the difference between the mean radiant temperature and the room air temperature.

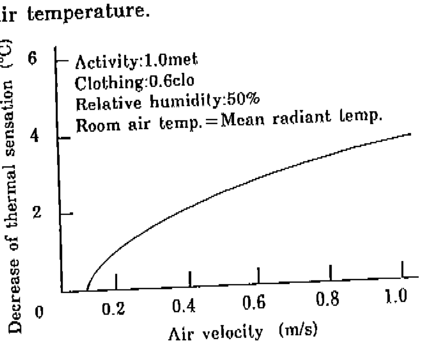


Fig.5 – Influence of air velocity for thermal sensation

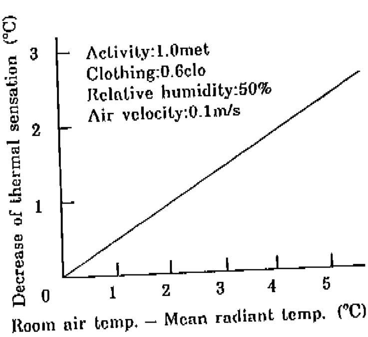


Fig.6 – Influence of radiation for thermal sensation

In the actual control, it is very difficult for the micro-computer in the indoor control unit to continuously calculate the SET* by the SET* theory due to the small ROM(Read Only Memory) capacity. Therefore, the SET* in the actual control is calculated using values of each thermal environmental factor. The example of the values is shown in Table 1.

Table.1 Influence of air velocity and humidity for thermal sensation

Air Velocity (V) (m/s)	ΔT_V (°C)
V≦0.2	0
0.2<V≦0.4	−1
0.4<V≦0.6	−2
0.6<V≦0.8	−3
0.8<V≦1.0	−3.5
1.0<V	−4

Relative Humidity(H) (%)	ΔT_H (°C)
H≦50%	0
50<H≦70%	1
70<H≦90%	2
90<H	3

The SET* in the air conditioning space is calculated approximately by following equation.

$$SET^* = T_R + \Delta T_V + \Delta T_H \quad (1)$$

T_R : mean radiant temperature

ΔT_V : difference of thermal sensation caused by the air velocity

ΔT_H : difference of thermal sensation caused by the humidity

The rotating speed of the compressor is adjusted according to the difference between the SET* calculated by eq.(1) and the preset SET*.

Fig.7 shows a comparison of results controlled by the SET* and by the room air temperature in the profiles of room air temperature, SET* and frequency of the compressor in heating operation.

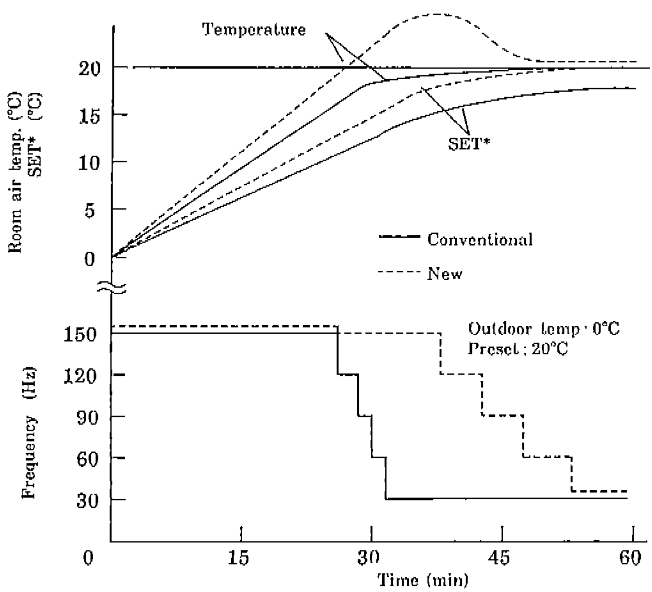


Fig.7—Comparison of results controlled by room air temperature and SET*

As is shown in the frequency profile, the frequency of the compressor controlled by the SET* is kept higher than that controlled by the room air temperature, because the SET* rises slower than the room air temperature due to the influence of radiation.
So, the time required for the room temperature and the SET* controlled by the SET* to reach 20°C is shorter than that controlled by the room air temperature.
It is obvious that the newly developed control is better than the conventional control when we consider thermal comfort.

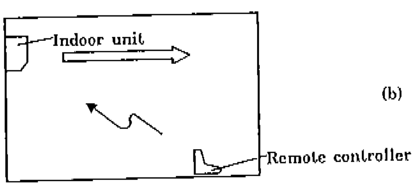
4.2 Automatically directional control of air flow (Heating operation)

As shown in Fig.5, the excessive air flow causes thermal discomfort.
Therefore, the automatically directional control of air flow so as not to make occupants feel draft has been investigated and applied to the actual control.
It is noted by A.TOYODA / 4 / that the directional control of air flow, especially in heating operation becomes important for the improvements of thermal comfort and the distribution of air flow.

However, the directional comfort of air flow using the air velocity sensor discussed in the previous section has not been applied practically, because the conventional air velocity sensor is not so compact and accurate as to be in practical use.
Using the sensor and the control which we developed in this work, the discharge air direction is automatically adjusted so as to make the air velocity around the remote controller less than 0.4m/s.

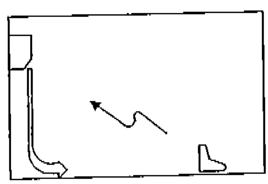
Fig.8 shows the movement of the horizontal flap according to this directional control.

(a)



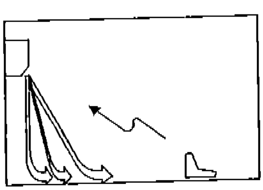
To prevent the non-heated air from direct bodily contact, the air flow is horizontally.

(b)



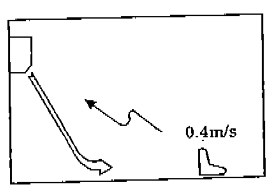
When the air temperature reaches 40°C or more, the heated air flow is vertical.

(c)



When the mean radiant temperature assumes to be 15°C or more, the heated air flow direction is varied gradually toward the center of room.

(d)



When the air velocity reaches 0.4m/s or more, the direction of the air flow is fixed.

Fig.8 – The directional control of air flow from start in heating operation.

In order to improve thermal comfort in the heating operation, the discharge air direction is controlled as follows.

(a) At the start of heating operation, the air is discharged horizontally in order to prevent the non-heated air from direct bodily contact.

(b) When the discharge air temperature reaches 40°C, the direction of discharge air is changed vertically in order to heat the floor without giving draft to the occupants.

(c) When the monitored SET* reaches 15°C or more, the direction of the discharge air is varied gradually toward the center of the room.

(d) When the air flow rate monitored by the air velocity sensor reaches more than 0.4m/s, the direction is fixed.

Fig.9 shows a comparison of the room air temperature, the SET* profiles and the air flow rate profiles around the remote controller. Comparing these profiles within 15 minutes from the start of operation, as for the rising speed of the room air temperature, the conventional control seems better than the new control. But, as for the SET*, the difference is not significant, because the SET* by the conventional control is decreased due to the higher air flow rate.
In this time, the occupants might feel discomfort by the higher air flow rate with the conventional control because the air flow temperature is lower /5/. Therefore, with the new directional control of air flow, thermal comfort can be slightly improved.

After 15 minutes, the SET* obtained by the new control is higher than that obtained by the conventional control.
The difference of these profiles occurs from the difference of the air flow rates.
Moreover, the thermal sensation obtained by the new control is better than that obtained by the conventional control because of the low air flow rate.
It is obvious from these results that the new directional control of air flow leads better effects on thermal comfort.

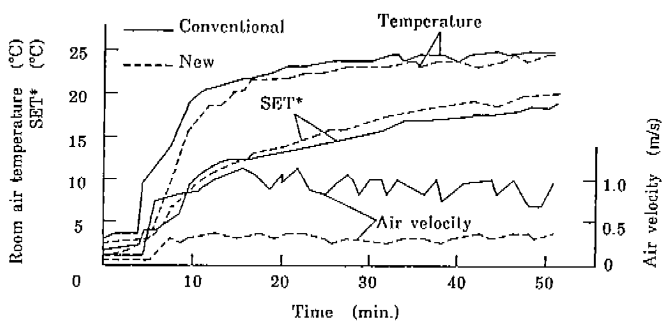


Fig.9 Variation of air temperature, SET* and air velocity around the remote controller

5. CONCLUSION

In order to improve the thermal comfort of the heat pump air conditioner for residential use, we have developed the radiation sensor and air flow sensor for the purpose of taking radiation and air flow in the control signals as the environmental factors.

Also, we have investigated the control systems using these sensors in addition to the conventional air temperature sensor.
Newly developed control systems include directional control of discharge air flow.
Applying these control systems to the air conditioner, thermal comfort has been improved in following respects.

(1) thermal control based on the SET* can be achieved.
(2) time required for room temperature to reach the preset value is largely reduced.
(3) discomfort due to the draft caused by the low temperature air flow can be excluded in heating operation.

We have made it clear that thermal comfort could be improved if the air conditioner is controlled with the signals based on the total environmental factors. In order to enlarge the field of heat pump air conditioner for residential use, much work will have to be undertaken.

Future work includes the investigation on the thermal sensation related to the activity of the man.

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SUMMARY

In recent years, inverter driven heat pumps are widely used for residential use as well as for industrial use.
Most of the conventional heat pump air conditioners have been controlled only by room air temperature as a thermal environmental factor.
However, it is a well know fact that thermal comfort is influenced not only by room air temperature but also by other thermal environmental factors such as air velocity, radiation and humidity.

In order to improve thermal comfort of the residential heat pump air conditioner, we have developed the sensors which can measure the above environmental factors and the control systems including the directional control of discharge air flow based on the data obtained from these sensors.

This newly developed control system was applied to the real operation of the heat pump room air conditioner and investigated through various experiments.
Thermal comfort has been improved significantly due to the SET* based control and discomfort cased by low temperature air flow can be excluded in heating operation.
In order to enlarge the field of heat pump air conditioned for residential use, much work will have to be undertaken.

Future work includes the investigation on the thermal sensation related to the activity of the man.