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S. Lassue
B. Duthoit
P. Théry

Université des Sciences de
Lille-Flandres-Artois, Laboratoire Capteurs
et Instrumentation, UFR IEEA,
Villeneuve d'Ascq, France

A Convective and Radiative Flux Sensor for Designing Thermal Comfort Controllers

Key Words
Thermal comfort
Radiative ambiances
Heat flux measurement
Feedforward control

Abstract

The recent scientific and technological progress in measuring heat flux has promoted new large-sized and short rise time sensors that are convenient for measurement on massive wall surfaces under unsteady-state conditions. The objective of this paper is to show the interest of measuring the energy balance on one of the massive parts of an enclosure to adjust the thermodynamic processes involved in air quality control in a given space. Another objective of the paper is to re-examine the procedure for the design of radiant heating control to show the interest of using radiative flux sensors in a feedback control loop. The radiative flux, which influences the energy balance of the room, provides a phase lead function, which can be used to control low-inertia radiant panels. Such a phase lead or feedforward control is adequate for identifying the effect of quick thermal disturbances on radiant temperature. Since no deviation from the equivalent temperature set point is required, such a feedforward control can be theoretically perfect in meeting thermal comfort requirements, depending only on the ability to detect the thermal disturbances from radiative measurements.

Introduction

One of the important tasks of climate research is to define the demands from or the expectations of indoor climate. For example, heat radiation, air temperature, air flow rate and humidity are some of the factors that affect heat balance. The common feature of relevant research is the use of the stimulus-response model for describing the impact of climate upon the body. In the classical control of an indoor environment, the ambiance quality is assessed by measuring one or several environmental parameters over time and calculating an index from a known equation to characterize the indoor climate. Such an index is considered as influencing an individual's heat balance and is used to integrate the cooling or heating influences of air temperature, mean radiant temperature and air velocity [1, 2]. Moreover, when the humidity is measured, the relevant humidity set point can be used for setting the controller [3] and even making allowances for other parameters, such as the clothing and activity of the occupants [4].

There are process conditions which can make the overall effectiveness of classical feedback control of the equivalent temperature quite unsatisfactory. One of these is the time required by the temperature sensor to detect energy inputs, which is an important factor in designing the controller performance, especially for a room having a long time delay. Another is the occurrence of thermal distur-

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Dr. S. Lassue
IUT de Béthune
Dépt. Génie Civil
F-62408 Béthune Cedex (France)

bances of large magnitude, such as a varying load caused by changes in the free heat during the day. The emphasis on 'changing' in describing such a control system indicates the non-steady-state basis for the design and adjustment of the thermodynamic processes involved in air quality control. The main objective of this paper is to show how new large-sized and short rise time radiative flux sensors can be used to adjust low-inertia radiant heating in a given space. The main advantage of using such sensors results from the observation that there is no necessity for a change to occur in the equivalent temperature before the control action takes place.

Radiative Heat Flux for Identifying the Unsteady Energetic State of Air in a Given Space

Introduction

Classical thermodynamics are concerned with the energy exchanges accompanying unbalances in the intensive properties of a system, for example in the air contained in a given space. Whenever a level of non-uniformity of the air, made up of space gradients of air temperature, air velocity, humidity and density, occurs in a given space or between a system and its surroundings, the force of unbalance will initiate a process that causes a change in the local energy state, and the direction of the change caused by the unbalanced force works to reduce the unbalanced driving potential. Classical thermodynamics is concerned with the local energy exchanges accompanying such unbalances in intensive properties, but is limited in that it deals only with the initial and final equilibrium states of a process and provides no information about the dynamic behavior between these states. However, it has long been known that an isothermal system undergoing transformation has a tendency to move in the direction of decreasing free energy. Moreover, in the case of non-uniform temperature and, more generally, of a space gradient of intensive properties, in accord with the requirement of the second law of thermodynamics, the entropy is the generalization of the concept of thermodynamic potential. In a previous paper [5], use of the entropy concept was extended to include heat transfers and then process heat flows and temperature changes as 'thermal signals', independently of their waveforms in the frequency domain. Essential in this formulation is the description of the local 'disequilibrium state' in terms of heat flow and temperature variations. In fact, that thermodynamic description of the local state of a system in terms of energy flow is general, since whenever an unbalance occurs in an intensive property, within the system or between the system and its boundary, the unbalance initiates an energy flow which is a distinguishing feature of the systemic evolution that is subject to measurement. Such a measurement will have great significance since it responds to changes in one or more of the dynamic variables used for the description of the system. The objective is to show the interest of that formulation in designing a thermal feedforward control strategy for the air quality in a given space.

Theoretical Basis for the Control System

As an example, consider a heated enclosure of surface S filled with a non-radiating material (fig. 1). When not in equilibrium, the enclosure is subject to both external and internal thermodynamic forces. The external forces may be considered as part of the enclosure and act to maintain temperature differences between the surfaces. Equilibrium thermodynamics postulates that there exists a state function, the internal energy, which is a function of the surface temperatures and is minimal in the reference state (or zero state) for which all temperatures are equal. On the other hand, due to internal 'disequilibrium forces', there is a net radiant energy transfer between surfaces. Under such circumstances, the energy emitted per unit time by the hotter surface (E_1) is larger than that emitted by the colder surface (E_2). To maintain the temperatures of the surfaces, an amount of energy $E_1 - E_2$ must be added to the hotter surface and an equal amount of energy extracted from the colder surface. There is thus a net energy transfer, and rather than attempting to extract a dynamic theory from the time derivative of the internal energy, it is more appropriate to start with a description in terms of energy flow, which may be considered as proportional to the derivatives of the generalized thermodynamic potential. In this example, the instantaneous direction of evolution of the enclosure is represented by the radiant energy transfer between the surfaces. Such radiant energy is transmitted without the need of a medium between the surface elements (fig. 1). If $\varnothing'_r dS$ is the radiant energy flux (energy per unit area and per unit time) arriving at surface dA from an element of surface dS of the enclosure, the total radiation arriving per unit area at dA is the radiant energy flux (energy per unit area per unit time) arriving at dA from all elements of surface dS. The total radiation arriving per unit area at dA is:

$$\varnothing_r = \int_S \varnothing'_r \, dS.$$

These terms lead to heat balance in the form of integral equations, and the radiative flux on the colder wall surface is expected to sense the unsteady radiant temperature of the whole enclosure. When radiation is combined with

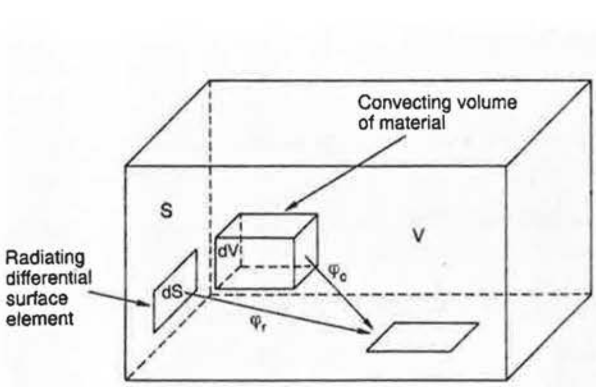


Fig. 1. Heated enclosure. φ_c = Convective heat flux; φ_r = radiative heat flux.

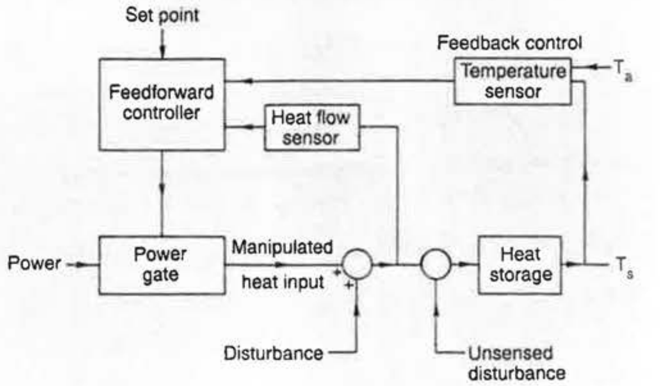


Fig. 2. Use of feedback control with feedforward control.

conduction and convection (i.e. whenever an unbalance occurs in an extensive property of the air within the system or between the system and its boundary, the disequilibrium force), it initiates an additional energy flux $\o_c$, which depends on the thermal gradients and physical properties in the immediate vicinity of surface dA. $\o_c$ is then a measure of the local heat balance (usually expressed in the form of differential equations). It must be noted that such a local measurement will have importance since it responds to changes in one or more of the dynamic variables used in the description of the air. Moreover, it can be noted that the radiative environment in which the surface exists (distance from corner, near the floor) affects the convection process and convective flux measurements indicating a geometric correlation.

From this analysis of the thermodynamic state of the air in a given space, it clearly appears that the temperature of a reference massive wall surface element and the convective and radiative flux through that element may be specified instead of specifying both the air and radiant temperatures at every time point. The wall surface element being in thermal contact with the other walls by convection and by radiation leads one to suggest that the heat flow components will depend on the geometry of the room, the distributed heat capacity of the building structure, instant values of the surface temperatures and radiative and convective thermal disturbances. For example, curtains, which partially or completely cover windows, may be expected to affect in several ways the heat balance of a wall near the window. The curtain could affect the convective air movements in the vicinity of the window, thereby influencing the local air temperature and, as a result, affect the heat loss in that area from the wall. The curtain would also be expected to affect the radiative interchange between the wall surface and the window glass that is low in temperature. Since the curtain may be expected to influence both components of the heat flux, the simultaneous measurement of radiative and convective heat flux components is quite adequate to detect convection and radiation. The purpose of such measurements is to detect a wide range of thermal disturbances, such as local shading, humidity, air velocity and wind break, and their direct influences on both components of the heat flux.

Thermal Feedforward Control from Radiative Flux Measurements

From a systemic point of view, it clearly appears that because of the long-wave redistribution between wall surfaces, the room envelope can be considered a self-regulating system in which the radiative flux acts to minimize the 'wall-to-wall' temperature differences. The radiative heat exchange is especially significant between massive and insulated wall surfaces under transient conditions when the temperature differences between insulated and massive walls (which are a cause of thermal discomfort) can be used to describe the thermal evolution of the envelope. The radiative flux, which influences the energy balance on a massive wall surface, then provides a phase lead function which can be used to control the air quality in the given space. Such a feedforward control can identify thermal disturbances affecting the wall surfaces and take corrective action with the intention of cancelling the effects of disturbances on radiant temperature. Since no deviation from the air quality set point is required, such a feedforward control can be theoretically perfect, depending only on its ability to measure the effects of thermal disturbances from radiative measurements (fig. 2).

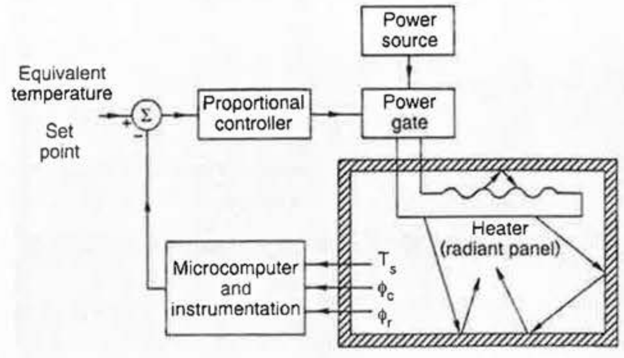


Fig. 3. Proportional controller converted into a resultant temperature programmable device (taking into account time delay of the room).

On the other hand, thermal storage in a massive wall is an integrating process, and any unsensed change in the total heat flux penetrating through the wall surface is expected to be integrated over a long period of time to increase or decrease the wall surface temperature. The surface temperature of the massive wall surface (T_s) is then an integrating (reset) action taking into account the time delay of the room, an action that is always required to eliminate the offset of the control. In this way, the plane radiant temperature of the enclosure (T_p, or the irradiance on a small plane element at the quasi-steady temperature T_s) is obtained from the classical relation:

$$ø_r = h_r(T_p - T_s) \text{ from which } T_p = T_s + \frac{ø_r}{h_r}.$$

T_p can be used in conjunction with the temperature T_s to estimate at all times the instantaneous average radiant temperature (T') by the following weighted summation:

$$(S_1 + S_2)T' = S_1 T_s + S_2 \left(T_s + \frac{ø_r}{h_r}\right),$$

S_1 and S_2 being, for example, the surface areas of the massive and insulated-wall sections,

$$T' = T_s + \frac{S_2}{(S_1 + S_2)\, h_r}\, ø_r.$$

The thermal state of the room is then expected to be represented by the following quantity:

$$T = \frac{1}{2}(T_a + T') = \frac{T_a + T_s}{2} + b\, ø_r.$$

Moreover, if the convection coefficient (h_c) near the wall is assumed to be known at all times from direct measurement [6], the air temperature is also obtained from the convective heat flux, and the thermal state is represented by the following expression:

$$T = T_s + a\, ø_c + b\, ø_r.$$

Through unsteady radiative and convective fluxes, the quasi-steady surface temperature T_s is supplemented to give a quantity T, which is expected to represent the air quality in the space under unsteady-state conditions. The feedforward controller, 'knowing' the energetic state of the system from the previous expression, then determines the required change in the manipulated heat input and heats so that when the effect of quick disturbances (detected by the flux sensors) is combined with the change in the manipulated energy input, there will be no change in the air quality (fig. 3). Since the energy balance on the massive wall surface is an integrating process, any unsensed flux or inaccuracies in the energy flux measurement (or in the associated instrumentation) will be detected by measuring T_s combined with the energy fluxes $ø_r$ and $ø_c$ in the feedforward strategy. Such a strategy based on energy flux measurements is well suited to manipulate low-inertia energy input in the presence of disturbances of large magnitude. On account of the terms ($a\, ø_c + b\, ø_r$), the index equivalent temperature does not need to deviate before a control action takes place. In such a feedforward control, radiative and connective disturbances are identified and measured before they affect the quantity to be controlled.

Application for Controlling Low-Inertia Radiant Heating Panels

Radiant heating systems (fig. 4) can be considered as a factor that influences surface heat balance, and they are designed to reduce heating costs by lowering the air temperature by between 1 and 2 °C, whilst at the same time improving the comfort level. In order to meet such objectives, the heating system must be accurately designed so that the exact energy input required of the room can be achieved. Saving can be accomplished if: (1) overheating of the room is avoided, and (2) advantage is taken of the total volume of energy generated by solar radiation, electric heating and machinery as well as the physical activity of the inhabitants.

When the previous expression is used to achieve control of the quantity T, the energy balance is made basically at the massive wall surface under steady-state conditions; such a strategy is a steady-state feedforward control. In practice, when electric power is dissipated in the radiant panel, the resultant change in the quantity T to be con-

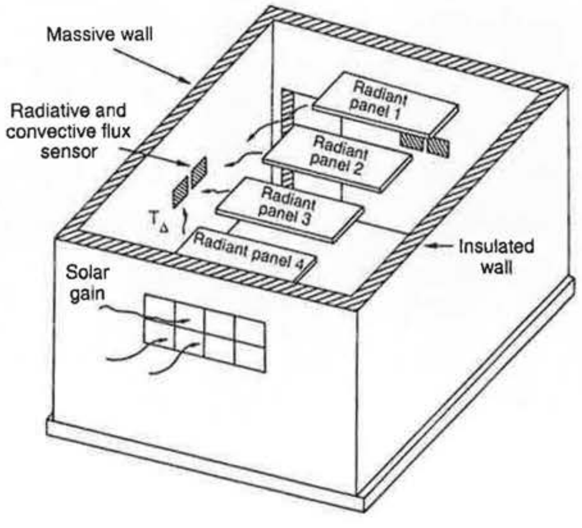


Fig. 4. Experimental room.

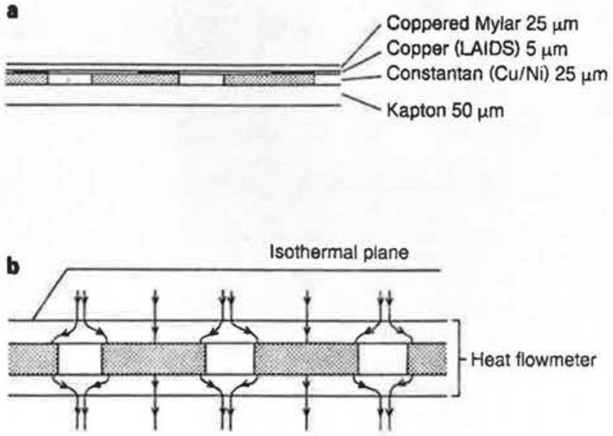


Fig. 5. Heat flow sensor.

trolled will not occur instantaneously. All techniques for determining system dynamics may thus be used to design a feedforward controller.

Heat Flow Sensor and Measurements

Principles

These sensors, contrived in our laboratory [7], have two main characteristics; they are very thin (0.1 mm) and highly sensitive (20 μV/W/m^2).

A Constantan (Cu/Ni) ribbon is placed on a kapton support, and then some dissymetrical elements of copper are put on it. This arrangement induces local perturbations of heat flux lines in the measurement plane producing a tangential gradient of temperature (fig. 5a). All the serially thermo-electric elements produce an electrical tension proportional to the heat flux through the sensor.

Two thin foils of coppered Mylar are laid on both faces of the sensor to obtain a uniform temperature on it (fig. 5b). Several works [8, 9] have shown that the effect of the heat flowmeter on measurement is generally negligible.

Radiative Heat Flux

A heat flux sensor placed on a wall gives a signal dependent on convective exchanges ($\varnothing_c$) between the surface and the air and on radiative exchanges ($\varnothing_R$) with the other walls. We have:

$$\varnothing = \varnothing_c + \varnothing_R,$$
$$\varnothing = h_c (T_a - T_s) + h_R (T_p - T_s).$$

When the sensor is covered with a low-emissivity thin foil, the heat flux approximates to pure convection. We can write:

$$\varnothing'_c = h_c (T_a - T_s'),$$

where T'_s is the new temperature of the sensor, and if we consider that the convective exchanges are not disturbed [6]. In this case, as we do not require excessive precision, this hypothesis is justified.

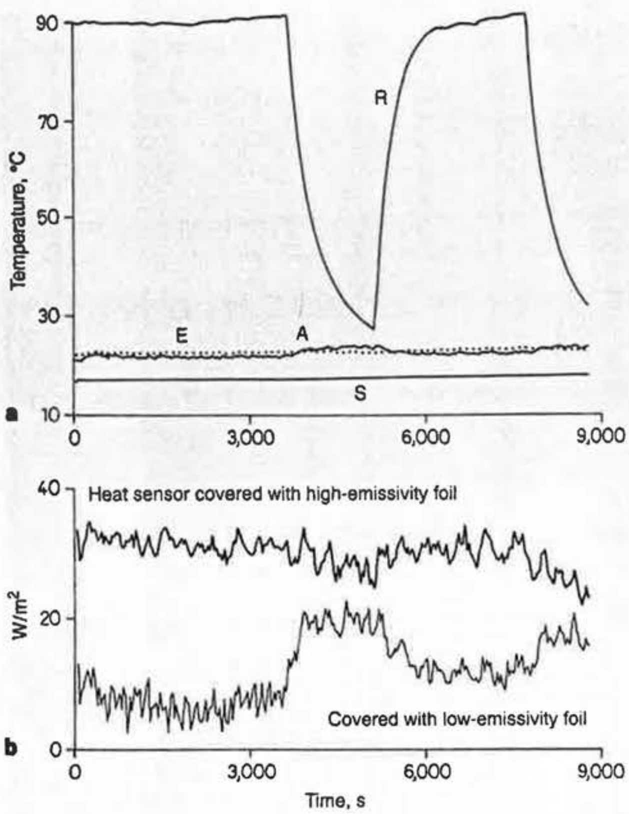
The sensors have a very small area, and the temperatures of the sensor T_s and T'_s are not very different. (This difference will depend on the nature of the wall supporting the sensor, i.e. whether it is concrete or insulated). If taking the difference $(T_s - T_s')$ into account to obtain the radiative heat flux, we can write:

$$\varnothing_R = \varnothing - \varnothing'_c \times \frac{(T_a - T_s)}{(T_a - T_s')}.$$

Results

Control System Analysis by Experiment

To analyse such a control system by experiment, it is necessary to separate the influences of air temperature and the thermal radiant environment in order to examine their respective influence on control capability.



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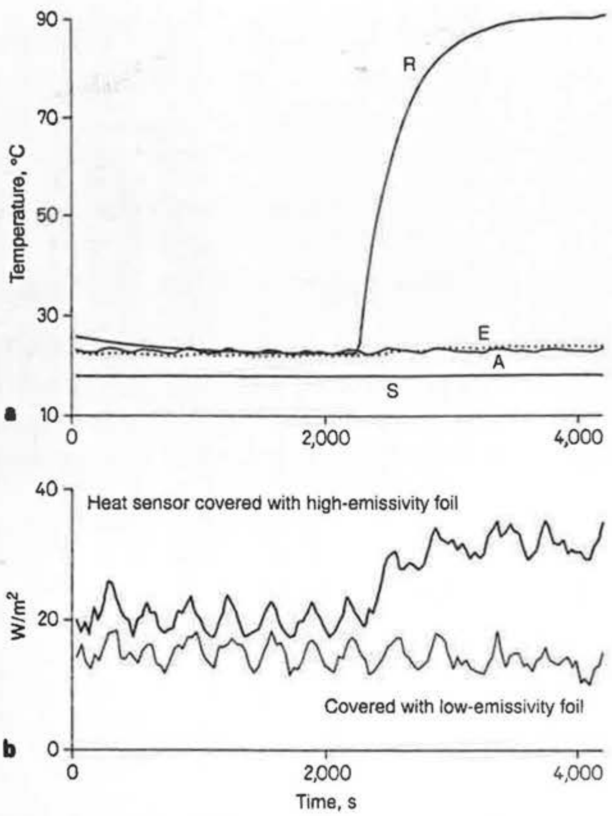

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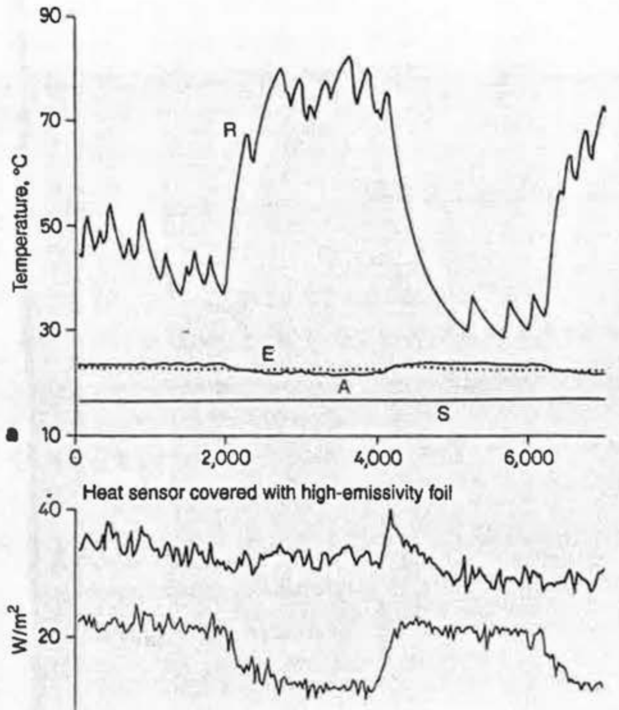

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Fig. 6. Proportional control of the air temperature to maintain the equivalent temperature at a constant set point. E = Equivalent temperature; A = air temperature; S = concrete wall surface temperature; R = radiant panel temperature.

Fig. 7. Proportional control of the temperature of radiant panels to maintain the equivalent temperature at a constant set point. E = Operative temperature; A = air temperature; S = wall surface temperature; R = radiant panels temperature.

Fig. 8. Classical control based on air temperature measurement and with radiative disturbances. Abbreviations as in figure 6.

The experimental room had a floor area of 7 × 5 m and 3-m-high walls. Four radiant panels (4 × 1 kW) were placed under the ceiling and four electric convectors on two opposite walls (fig. 4). Thus, the main driving forces were the air temperature and the radiant temperature partially controlled by means of radiant heating panels. Different free heat inputs could be introduced into the room in order to simulate solar gain, emission of heat from occupants and electric lighting. The room air temperature and equivalent temperature were measured in the centre of the room with a black globe. The walls of the room as well as the radiant panels were fitted with thermocouples at their geometric centres to measure the temperatures at these locations. Two heat flow sensors covered with thin foils of contrasting emissivities were placed on the concrete wall to measure the radiative heat flow with the sensitivities of the sensors being known ($20\ \mu V/W/m^2$). The first object was to show that the increase in the mean radiant temperature could be compensated for by a decrease in the indoor air temperature and conversely. The combination of air and surface temperatures and radiative flux has been tested as the measurement associated with a proportional controller for a quick and correct reaction on changes in the index T. The measured quantity was used to manipulate the heating sources.

From the supposition that maintaining the index T at a constant set point gives an indication of the ability of the control procedure to provide comfort and avoid unnecessary use of energy in the actual situation, then from figure 6, it can be seen that in the tested system, no deviation from the equivalent temperature set point is required to cancel the effect of radiative thermal disturbances by means of adequate air temperature changes. Similarly (fig. 7), when the indoor air temperature decreases, it is possible to increase the mean radiant temperature adequately by using the radiant panels located in the upper zone of the test chamber. From figure 8, it can be seen that the limits of a classical control based on air temperature measurement are: (1) the time delay of the room as it induces an air temperature deviation from the set point and (2) radiative disturbances that are not 'seen' by the controller.

Conclusions

From the previous considerations, a low-inertia radiant ceiling is suitable for the control, based on radiative heat flux measurements, of a quick radiative heat input which represents direct and indirect radiative heating effects of insulation through cell heat paths. The control results indicate that the control process is very fast and the overshoot very small and that the deviation in the radiant temperature can be eliminated quickly.

The main advantages of the control strategy developed in this paper are:

1 the simplicity of the basic concept;
2 the microcomputed instrumentation based on heat flow measurement converting a proportional controller into an equivalent temperature programmable device taking the time delay of the room into account;
3 the lack of necessity for the equivalent temperature to deviate before a control action takes place, and
4 the detection of the ambiance radiative aspect.

So, with a low cost controller, it is possible to improve an indoor climate and avoid overheating.

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