LITERATURE STUDY ON RADIANT HEATING

IN A THERMALLY- COMFORTABLE INDOOR ENVIRONMENT:

A SUMMARY REPORT

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A. Introduction

The main purpose of heating and air conditioning commercial and residential spaces is to provide an indoor environment that is generally acceptable and does not impair the health and productivity of the occupants. Currently, considerable research is being devoted to finding the most energy-efficient method for heating spaces while maintaining acceptable thermal comfort conditions. One system that has been recently given attention to is the use of infrared radiant (IR) heaters that can be powered by gas, oil or electricity. If correctly designed with consideration of all the standard parameters, IR heating systems can provide optimal microclimatic conditions within the whole heated space.

B. Radiant heaters vs. convective heaters

Radiant and convective heating systems produce different thermal comfort environments and generally differ in energy consumption due to their nature of heat delivery or removal.

Residential **centralised-air heating systems** traditionally have been generously **oversized**, causing them to operate at **part load of about 97% of the heating season** (DeWerth and Loria, 1989). To save energy, a centrally-heated home (e.g. warm air furnace or boiler) usually uses the technique of **excluding or controlling heat for certain areas** but this often results in **uncomfortable areas** of the home. In this case, one solution to **increase the overall comfort and reduce energy consumption at the same time** is to provide a **source of supplemental heat** to those areas being occupied at one moment and **exclude or lower the overall supply of central heat**. Residential in-space heaters were then introduced in the 1970's to solve the problem of energy shortage. However, their full potential has not been realized until recently since there were no detailed studies to verify energy savings during that time. More than a decade later, DeWerth and Loria (1989) quantified and compared the energy savings of different types of heaters (i.e. **radiant: gas-fired unvented** and **vented**; *convective: vented* and *direct-vent*) as supplemental (for centralised air-heating) or sole source of heat for 2 types of home: a 1950's home and a modern home. Results showed that the **in-space heaters** used **less energy (gas or electric)** than the central system, e.g. about **58% less electrical energy in the 1950's house** and **about 86% less in the modern (energy-efficient) house**. Comparing both **radiant-type** and *convective-type* in-space heaters showed that using the **radiant-type saved more** than its counterpart, i.e. **25% more** in the 1950's house and **10% more** in the modern house.

Numerous researches on radiant heating systems have followed then, mostly evaluating the advantages and disadvantages of this type of heating system and comparing with the traditional convective heating system. In general, these studies proved that ***radiant heating*** systems offer the potential of **(1) reduced heating unit sizes** (due to reduced heat load and peak load), **(2) reduced energy consumption** (Zmeureanu et al., 1988; Howell and Suryanarayana, 1990; Imanari et al., 1999; Petras and Kalus, 2000; Miriel et al., 2002; Feng et al., 2006) and **(3) favorable tie-in capabilities with low-temperature and low-intensity energy sources** such as solar systems and heat pumps (Kilkis et al., 1995) **(4) while maintaining acceptable thermal comfort** (Imanari et al., 1999). Compared to convective heaters, ***radiant heaters*** may be **operated at a lower air**

temperature (Hart, 1981; Zmeureanu et al., 1988; Howell and Suryanarayana, 1990; Kalisperis et al., 1990; Ling and Deffenbaugh, 1990) because the radiant heat from the heater falls directly (or indirectly through surfaces) on the occupants thus **producing more comfortable conditions**. This means that ***radiant heating*** systems increase the mean radiant temperature (MRT; average room surface temperature) to which occupants are exposed, thereby allowing **comfort at lower temperatures**. Thus, it is possible to **maintain the air temperature by 5°C lower** compared to classical methods at the **same comfort level** (Dudkiewicz and Jezowiecki, 2009).

On the other hand, a *convective heating system* produces an environment where the *air temperature is greater than the MRT in space*. For this reason, *infiltration losses are greater* than in radiant heating systems (Hart, 1981; Zmeureanu et al., 1988) which is not favorable since air infiltration rate in a building is one of the significant factors affecting energy use and comfort (DeWerth and Loria, 1989). Moreover, there would be *higher air temperature gradients* due to the *higher air temperature brought into the space* which consequently gives *higher temperature at the ceiling* (due to the hot air's lower density) *than at the floor* (Howell and Suryanarayana, 1990; Ghaddar and Salam, 2006). Since the overall thermal comfort sensation tend to decrease with an increase in the magnitude of environmental thermal non-uniformity (Sakoi et al., 2007), *higher air temperature gradients* can also lead to a *lack of spatial uniformity of thermal comfort* in the given space (Kalisperis et al. 1990). Conventional systems that uses air as the transport medium *has lower (maximum) potential for delivering sufficient heating/ cooling* since it is limited to the thermal capacity of the air and its ability to transfer thermal energy (thermal conductivity and air flow rate) to or from a surface (Ardehali et al., 2004). Thus *convective heating* systems typically *respond slower* especially to step (temperature) changes (Berglund et a., 1982) and *a rise in air temperature by 1°C could mean a 6% increase in energy consumption* (Roth et al., 2007).

C. More advantages (and disadvantages) of radiant heating

Maintaining thermal comfort

Panel location can significantly affect the magnitude and distribution of room surface temperatures (MRT) and thereby affect required heater capacity necessary to achieve a given comfort level. When units are properly-sized and located, **a higher MRT for the occupants is produced which then permits a lower air temperature for equal comfort conditions**. However, if the radiant heat is too concentrated such that the asymmetric temperature (difference between the plane radiant temperatures of the opposite sides of a small plane element (ASHRAE, 2009)) is too much felt by the occupant then (local) discomfort occurs (Howell and Suryanarayana, 1990; Dudkiewicz and Jezowiecki, 2009). Normally, discomfort should not be experienced by occupants in spaces heated by radiant systems if thermal comfort equations (e.g. Fanger's) are satisfied and the asymmetric temperature is limited to 9°C (Howell and Suryanarayana, 1990).

Energy efficiency

Radiative transfer between the occupant and surrounding surfaces benefits from the difference in the fourth power of the temperatures as compared to the heat exchange by convection between the occupant and the adjacent air, which **varies linearly with**

temperature difference (Ardehali et al., 2005). A study made by Kilkis (1992) showed that r**adiant heating** can also **increase the efficiency of a heat pump system**. Zmeureanu et al. (1988) found out that the **heat load** and **peak load of a radiant heating system was lower (77% and 80%, respectively) than *conventional systems* at the same level of thermal comfort**. Since part of the sensible thermal load is handled by radiant ceiling panels, **volume of supplied air can be reduced** which in turn can **reduce air transport energy (by 20%)**. This saving reflects a **total energy consumption of 10% less than a *conventional convective* system** (Imanari et al., 1999; Miriel et al., 2002). **Further savings** can be benefited with the use of radiant heaters by means of **installing fast-acting surface mounted-radiant panels**. Watson et al. (1998) used a multi-sized ceiling-mounted radiant heater with higher watt density of 50 W/ft^2 sized to the nearest 100 W of heated area and found **significantly lower retrofit installed and maintenance costs compared to other types of heaters**.

However, since radiant heating systems heat surfaces instead of the air in the room, higher surface temperatures (wall, floor, glass) occur and produce greater heat losses through the surfaces to the outside (transmission losses) (Hart, 1981; Howell and Suryanarayana, 1990). This can be compensated by ensuring that the heated space is well-insulated.

<u>Reduced air temperature gradient</u>

Since **radiant heating systems heat surfaces**, there is **very little air motion** resulting in a **more uniform room air temperature distribution** (Howell and Suryanarayana, 1990; Imanari et al., 1999; Miriel et al., 2002). This can lead to a **more uniform distribution of thermal comfort (in terms of PMV values)** within the occupied zone and **reduction of energy requirements** (Ling and Deffenbaugh, 1990).

<u>Healthier air</u>

Utilisation of thermal radiation to condition air **reduces the dependency on air as the thermal transport mechanism** while passing indoor air quality requirements (Miriel et al., 2002; Ardehali et al., 2005; Feng et al., 2006; Ghaddar and Salam, 2006). Thus, allergens (e.g. mold spores, dust, insects, pollens) and disease-causing microorganisms usually carried by the heated air medium can be reduced if not totally avoided. This advantage gives radiant heating systems an edge to **wider range of applications,** from residential and commercial buildings to buildings requiring higher indoor hygiene (e.g. hospitals, clinics, nursing homes, etc.).

<u>Convenient operation</u>

Complications attributed to circulating high volumes of air (e.g. more wiring, pipes, ducts and other installations) **are avoided** with radiant heating systems (Ardehali et al., 2005).

<u>Efficiency of space use</u>

The space consumed by a radiant heating system, be it hydronic or electrical, is less than that of a variable-air-volume (VAV) system (Simmonds, 1996).

Zoning

Radiant heating panels can be installed in such a way as to **provide zoning or conveniently placed in a location that needs radiant compensation** (Simmonds, 1996).

D. Radiative-convective hybrid systems

This system combines the heat transport benefits from both systems wherein low-turbulence air supply will be used. The convection system will only be used for air renewal and humidity control thus reducing fan transportation energy. Cooling is provided mainly by radiation as well as the majority of the thermal load. This type can provide more stable levels of year-round comfort, cleaner surfaces, more uniform air temperatures and a healthier environment (Scheatzle, 1996).

E. Design of radiant heating panels

Sizing and position of units

A variety of approaches can be used to determine the sizing of a radiant heater installation (DeWerth and Loria, 1989). However, there is not yet a specific standard for sizing and positioning radiant heating systems. ASHRAE Fundamentals (ASHRAE, 2009) provide a standard heating load design procedure but its applicability to radiant systems still require more validation studies. Aside from a guideline available for the requirements to generate uniform thermal field and to provide thermal comfort to the occupants, no information is known to be available in literature about the determination of thermal conditions in spaces heated by IR heaters (Dudkiewicz and Jezowiecki, 2009). In general, designers often rely on the calculation techniques provided by the manufacturers of radiant heaters on how to estimate the number of units that one can install in a given space.

There are, however, several studies which give recommendations on how to size (e.g. dimensions and number of units) heating systems (DeWerth and Loria, 1989; Howell and Suryanarayana, 1990) and how to position the radiant heaters (e.g. installation height, inclination angle, etc.) to produce thermal comfort conditions (Dudkiewicz and Jezowiecki, 2009). Based on the finding that the **resultant temperature at the top of an occupant's skull must not exceed 25 °C**, Petras and Kalus (2000) developed an equation to compute the **smallest acceptable installation height of IR heaters as a function of heater size, indoor air temperature, maximum radiation flux density, surface temperature of the heater, and the radiation surface material constant**.

Importance was also given to the **estimation of design heat loss value** so that heating units can be sized and located properly. **Emissivity, convection coefficient** and **U-factor** should be specified for all surfaces. **Higher U-factors lead to increased heat loss and greater panel area required**. In general, the **required area for heating with panels is reduced as panel heating surface temperature increases**, e.g. 49% of the ceiling area was covered with radiant panels with surface temperature of about 49°C while 20% was covered with radiant panels with surface temperature of 82°C. Moreover, as **room height increases, more panel area** is required to counteract the increased heat loss in the room. Because of room geometry change, more of the walls intercept the radiant energy and thus increases the average unheated surface temperature (Howell and Suryanarayana, 1990).

Energy transfer mechanisms and heat transfer models

There are several ways to evaluate the performance of a radiant panel. One of them is the computation of total heat flux from radiative and convective heat transfers, which can be computed both numerically and with the use of empirical relations that accounts for the radiative and convective heat transfer from a panel with a homogeneous surface temperature (Ardehali et al., 2004). With radiant ceiling panels, both radiation and convection constitute the major mode of heat transfer from the surface of the panels to the air space being heated. Convection in panel systems is usually considered to be free convection caused by air motion due to induced buoyancy (Zhang and Pate, 1989).

In a study made by Kilkis et al. (1995), the **heat output of a radiant panel depends on the indoor air temperature, surface temperatures of all unheated surfaces, air movement in the heated space**, and other **surface characteristics (e.g. emissivity)**. The convective part of the heat output depends on altitude and size of the conditioned space. If these factors are adequately correlated, the **total heat output** can be expressed in terms of **panel surface temperature** only and the **total panel heat output intensity is the sum of radiant and convective heat output intensities** (Kilkis, 1992). A **higher panel surface temperature** results in a **lower combined flux (radiative and conductive) from the panel** for a given ambient temperature. Moreover, this **combined flux for the panel increases with increasing ambient temperature** (Ardehali et al., 2004).

Energy transfer by radiation decouples heat transfer mechanisms from the ventilation function of the building air without sacrificing the thermal comfort of occupants. This **decoupling** is responsible for a **higher energy efficiency achieved** when radiant heating/ cooling systems are used (Ardehali et al., 2004). More studies have been made to better understand heat and energy transfer mechanisms in radiant heating systems. Models describing these mechanisms were developed and were validated against standards and other types of heat transfer model.

Testing radiant panels

There are several standards to test radiant heating panels. Appendix Table 2 lists some of the standards on testing and rating radiant heating panels. Another standard not listed but also often used is DIN 4706-1-1993 (Ceiling Mounted Radiant Panels – Part 1: Test Specifications) (Kochendorfer, 1996).

Control system

Technological developments in sensors and microprocessors make a higher standard of comfort control possible using radiant heating systems. Sensors have recently become more reliable and relatively expensive as they become mass-produced. The same is true with microprocessors, which allow more sophisticated decision-making and can use expert system methods for selecting and operating the most appropriate system at its optimum performance (Scheatzle, 1996). Studies in this field had been done to **incorporate thermal comfort parameters in the control loop** to ensure **an acceptable and stable indoor environment** with the **lowest energy consumption** possible. Two major concepts of control have come from these studies: **PMV (Predicted Mean Vote) control** and **operative control**.

Predictive Mean Vote (PMV) Control. PMV predicts how the "average" person would vote using the ASHRAE thermal sensation scale. Predicted Percentage Dissatisfied (PPD), which can be calculated from the PMV index, is the predicted percentage of people expressing dissatisfaction with a given thermal environment (Schiller, 1990). The predictive mathematical model, which was based on PMV index, developed by Fanger (1982) can be used to design a device for controlling comfort, hence called a comfortstat. Similar to a thermostat, a comfortstat would maintain conditions within a range of acceptable values. Additionally, since it is based on the six factors influencing PMV, a comfortstat can control additional devices that affect not only the ambient air temperature but also radiant temperature, air motion and humidity (Scheatzle, 1996). Lin et al. (2002) developed a **multi-sensor single-actuator HVAC** controller based on PMV-PPD which can **simultaneously improve thermal comfort (from 30% to 20% PPD) and energy consumption (by 17%)**. Another PMV controller which implements a **model-based predictive control system** was developed by Freire et al. (2008) to adapt to individual parameters while providing better global performance in terms of both **thermal comfort control and energy consumption reduction**. PMV control was already applied to traditional electric air-heating system (Conceicao and Lucio, 2008) and thus using PMV index for control can also be possible for a simpler radiant panel heating system.

Operative Sensor Control. A control system can also be designed based on **operative temperature (OT)** alone. The operative temperature, whose value is very close to the air temperature, is the uniform temperature of an enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment. It is a combination of two primary variables in most sedentary comfort conditions, i.e. **ambient air temperature** and **mean radiant temperature (MRT)**. MRT plays a major role in evaluating comfort when using radiant systems (Scheatzle, 1996) and thus should be accurately determined. Determining OT also requires the knowledge of the **radiant panel surface temperature** (Zhang and Pate, 1989) since an **increase in radiant panel surface temperature (intensity) should be compensated by a decrease in air temperature in order to maintain constant operative temperature and occupant's thermal comfort** (Fanger, 1982). Studies compared the use of operative temperature and air temperature to control radiant heating ceilings in climate chambers during transient conditions (Berglund et al., 1982) and steady-state conditions (Athienitis and Shou, 1991) and similar findings were obtained. **Compared to an air temperature-based controller (which is commonly used in convective heating systems), the use of operative temperature control resulted to (1) none or less overheating (overshoot) contributing to 10 to 12% energy savings, (2) greater thermal acceptability by the occupants, (3) faster response and (4) less overheating at the head region**.

II. Thermal Comfort

A. Introduction

As defined by ASHRAE Standard 55-2004, thermal comfort is that condition of the mind that expresses satisfaction with the thermal environment (ASHRAE, 2009). Individual comfort assessment is thus a cognitive process that involves many inputs influenced by physical, physiological, psychological and other factors. Fanger (1982) merged physiological theory and statistical evidence of human response and developed a predictive mathematical model of thermal sensation. According to Fanger, six comfort variables (activity level, clothing insulation, ambient air temperature, mean radiant temperature, air velocity and relative humidity) produce a single index that can be used to predict comfort conditions, i.e. Predicted Mean Vote (PMV). Fanger (1970) defined the Predicted Mean Vote (PMV) as the index that predicts or represents the mean thermal sensation vote on a standard scale for a large group of persons for any given combination of the thermal environment variables (air temperature, air humidity, air velocity and MRT), and the personal variables (activity level and clothing insulation). Each of these variables can be measured using references or consulted from international standards. Olesen (1995) presented a comprehensive list of these standards. ISO 9920-1993 contains a large database of thermal insulation values for clothing ensembles and individual garments, which resulted from measurements done on a standard thermal manikin. ISO 8996-1989 gives the ergonomics to determine the metabolic heat production since all thermal environment assessments require an estimate of the occupants' metabolic rate which reflects body activity level.

All the environmental variables can vary temporally as well as spatially with respect to the occupant's body (Jones, 2002). Sakoi et al. (2006) recognised that except for "activity level", all the factors from the PMV model influence the thermal state of a human being through the heat transfer processes at the skin surface and can be described by the relationships among human perception and the physiological thermal state of the skin (e.g. skin temperature, skin wettedness, etc.). This physiological thermal state is then considered closely related to thermal sensation and thermal comfort.

B. Factors influencing (local) thermal discomfort

In the earlier years of thermal comfort studies, comfort was often described as affected by the occupant's thermal sensation by the whole body. But aside from the overall thermal state of the body (general body comfort), an occupant may also find the thermal environment unacceptable if local influences on the body from (i) asymmetric radiation, (ii) draught, (iii) vertical air temperature differences, or (iv) contact with hot or cold surfaces are experienced (Olesen, 1995; Kalisperis et al., 1998; Olesen and Brager, 2004; de Dear, 2004). Thus, it is necessary to study the localised effect of each thermal comfort variable on the human thermoregulation to obtain an adequate thermal comfort assessment (Orosa, 2009).

Radiant temperature asymmetry. Radiant temperature asymmetry is the difference between the maximum and the minimum radiant temperature on the surfaces of a cube element located at a point in the space being conditioned (Dudkiewicz and Jezowiecki, 2009). Because ceilings are farther from the occupants than floors, standards set ceiling temperature limits in terms of radiant temperature asymmetry (Wang et al., 2009). The permissible value for a warm ceiling is

5 K (ASHRAE 55-2004; ISO 7730, 2005). However, studies showed that values might be higher than the standards, depending on the type of heater, its surface temperature, size and position in the space being conditioned (Olesen and Parsons, 2002; Dudkiewicz and Jezowiecki, 2009).

Draft. Draft is the unwanted local cooling of the body caused by air movement (Olesen and Brager, 2004). It is one of the most critical factors since many people are sensitive to air velocities (e.g. to changes or fluctuations) thus making it a very common cause of occupant complaints in ventilated and air-conditioned spaces (Olesen, 1995).

Vertical air temperature difference. A high vertical air temperature difference between the ankle and the head usually cause discomfort (Olesen and Parsons, 2002). This often occurs in centralised air-heating systems but might also occur in other types of incorrectly designed heating systems.

Floor surface temperature. This is especially important for thermal comfort assessment of spaces with occupants wearing light indoor shoes or in cases where occupants sit/ lie on the floor or walk indoors with bare feet as in common in Asia (Olesen and Parsons, 2002).

C. Thermal comfort measurement and evaluation

Thermal comfort models

Prediction of thermal sensation can be based on several models found in literature and global standards. The most commonly used in thermal comfort studies include (i) PMV-PPD (Fanger, 1970), (ii) PMV_G-PPD_G (Gagge et al., 1986), and (iii) TSENS (Gagge et al., 1972). The PMV-PPD model is useful only for predicting steady-state comfort responses. The PMV_G-PPD_G model is a modified PMV-PPD two-node model developed by Gagge et al. (1986) which can be used to predict physiological responses in transient conditions. TSENS (thermal sensation) is based on the same comfort scale as PMV (7-point scale) but with extra terms for extreme sensations (i.e. ± 4 (very hot/ cold) ± 5 (intolerably hot/ cold)) (ASHRAE, 2009).

These mathematical models are based on combined theoretical and empirical equations which describe (a) the heat and moisture exchange between the occupant's body and the environment in either steady-sate or transient heat balance, (b) the physiological thermoregulation mechanisms of the body, and (c) the relationship between the occupant's thermal sensation (psychological response) and the physiological thermal strain on the body due to environmental and personal conditions (Schiller, 1990; Jones, 2002).

There are different approaches to evaluate thermal comfort: (i) the traditional "static" Fanger approach based on the PMV index and (ii) the new "dynamic" adaptive comfort approach based on de Dear and Brager. The "static" approach defines small intervals of acceptable temperatures and suits *fully mechanically-controlled* buildings while the "dynamic" approach defines wider intervals of acceptable temperatures and suits *not fully mechanically-controlled* buildings (Corgnati et al., 2008). The PMV index is best applied to evaluation of moderate thermal environments (Olesen, 1995) and is generally used for predicting general thermal comfort.

With all these models and approaches to estimate thermal comfort, the big challenge is now on responding to the critical need to provide a thermal comfort evaluation framework developed from empirical knowledge based on laboratory and field studies around the world over the last 40 years and the algorithmic implementation of mathematical thermal comfort prediction models. As an answer to this challenge, researchers have been developing tools for assessment of thermal environments. These tools were made available based on numeric procedures that follow relevant ISO standards while implementing thermal comfort mathematical models. Thermal comfort calculations can already be integrated in a computer-aided architectural design environment just like any other performance simulation (Kumar and Mahdavi, 1999; 2001). Several software programs were developed as tools to evaluate thermal sensation indexes (Alfano et al., 2005) while online databases were made available in some countries for building designers, consultants and customers (van der Linden et al., 2006). Comfort values and scales were also developed for building energy simulation programs for thermal comfort assessment in residential buildings (Peeters et al., 2009).

Instruments and measurements

There are two methods of evaluating compliance with comfort requirements: (i) analysis of environmental variables and corresponding body (physiological) responses to determine comfort conditions and (ii) occupant survey. ISO 7726-1994 lists a description of parameters that should be measured together with the methods and specifications for the instruments in order to accurately evaluate a thermal environment (Olesen, 1995; Olesen and Brager, 2004).

Environmental measurements. Physical measurements of environmental variables (i.e. air temperature, air humidity, air velocity and MRT) can be done using standard measuring instruments based on ISO 7726-1994 (Olesen, 1995).

Physiological measurements. The principles, methods and interpretation of measurement of related human bio-responses (i.e. body core temperature, skin temperature, heart rates and body mass loss) to hot, cold and moderate thermal environments are shown in ISO 9886-1989. This can be applied to extreme cases where occupants are exposed to severe environments or in laboratory investigations (Olesen, 1995).

Subjective measurements. Aside from giving examples of scales that can be used to assess thermal environments, ISO 10551-1995 also contains the principles and methodology behind the construction and use of subjective scales. Safety of human exposures to either hot or cold thermal environments is the primary concern of the medical screening standard and advices given by ISO/ DIS 12894-1994 (Olesen, 1995). Lee et al. (2010) studied the validity of a combined categorical scale (CS) and visual analog scale (VAS), i.e. (graphic CS), to evaluate subjective thermal responses and found out that graphic CS was more valid and sensitive than a 9-points CS or VAS to measure thermal sensation.

Thermal comfort studies can be grouped into two based on their methodology in conducting comfort variable measurements: (i) laboratory-based studies and (ii) field studies. Laboratory-based methods (climate chambers), such as that of Fanger's research (1970), have evolved into deterministic stimulus-response standards (e.g. EN ISO 7730-2005) while field-based researches were based on a holistic person-environment systems approach to comfort standards (e.g. Adaptive Comfort Standard or ACS). De Dear (2004) presented an overview of the key differences between the two methods along with the implications for thermal comfort in practice. A comparison of these two methods is shown in Table 1. Several studies were also done to determine the extent to which theoretical and laboratory-based equations accurately predict occupants' thermal responses in existing residential and commercial spaces (Schiller, 1990).

Table 1. Comparison of thermal comfort research in climate chambers and field-based.

	Climate Chamber	**Field Study**
Approach	Deterministic stimulus-response 'engineering' approach	Holistic person-environment 'architectural' approach
Research location/ setting	Laboratories (university) at mid-latitude climatic zones of North America and Northern Europe	Actual buildings located in a cross-section of climate zones across the globe - hot, dry desert - temperate mid-latitude - tropical
Subjects	Mainly university students Average size: 16 per exposure	Mainly occupants of commercial office buildings
Standards	EN ISO 7730: 2005	ASHRAE Standard 55: 2004
Major contribution to standards	Isolated key environmental parameters of the indoor thermal environment and relevant personal parameters	Concept of adaptive thermal comfort model in naturally-conditioned buildings
Standard applications	• Centrally air-conditioned buildings • Occupants activity (< 1.2 met) • Clothing: ~0.5 clo (summer) ~1.0 clo (winter)	• Centrally-conditioned and naturally-conditioned buildings • Occupant activity (1.0 – 1.3 met)
Advantages	Excellent control over environmental conditions	• Involves actual buildings under normal occupancy • Larger, diverse samples of 'real' occupants • Energy demand can be reduced to 50% with PPD<10% (Corgnati et al., 2008)
Disadvantages/ Limitations	No method yet to assess how dissatisfaction from multiple sources are combined	Lower control in measuring physical environmental variables

D. Adaptation and naturally-conditioned buildings (Adaptive Comfort Model)

An extended PMV model was later developed by Fanger and Toftum (2002) which includes an expectancy factor for predicting thermal comfort in non-air-conditioned (naturally-conditioned) buildings in warmer climates. When the expectancy factor is low, the model predicts a higher upper temperature limit (e.g. 2°C change) since occupants used to warmer environment have low expectations and are ready to accept a warmer indoor environment. The results were coherent with the study conducted by de Dear and Bragger (2002) regarding the adaptive thermal comfort model. Since then, the adaptive thermal comfort studies have been given significant attention and results were incorporated in international standards such as ASHRAE 55-2004 as well as in national guidelines and future building design considerations in some countries (van der Linden et al., 2006; Karjalainen, 2009).

E. International standards and the ergonomics of thermal environment

Standard methods are necessary so that different solutions and evaluations of thermal environment can be done in a comparable way. Presently, global standards set by international organisations such as ISO (International Organization for Standardization), ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers) and CEN (European Committee for Standardization) include (a) evaluation methods for moderate, hot, and cold environments, (b) supporting standards for measuring and determination of relevant parameters, and (c) standards for measurement and evaluation of individual physiological conditions of humans (Olesen, 1995; Olesen and Parsons, 2002). Recommended limit values given by these standards, may then be adapted by local standard organisations (e.g. Bureau de Normalisation (NBN) and Belgian Electrotechnical Committee (BEC) in Belgium and Nordic Committee on Building Regulations (NKB) in the Scandinavian countries) within national rules for thermal environments. A comprehensive overview of existing and upcoming international standards related to assessment of thermal environments and radiant heating, respectively (CEN, 2010) is presented in Appendix Table 1 and Appendix Table 2.

The main thermal comfort standard used in assessing moderate thermal environments is ISO 7730 based on PMV/ PPD of Fanger (1970). It includes methods to assess local discomfort caused by draughts, asymmetric radiation and temperature gradients. An example of the recommended limits for moderate thermal environment is shown in Table 2. An equivalent Heat Stress standard (ISO 7243: 2003) is used in hot environments based on the wet bulb globe temperature index (WBGT) (Parsons, 2006). Technical specifications are also provided in standards for thermal comfort for people with special requirements (ISO TS 14415), responses on contact with surfaces at moderate temperature (ISO 13732: 2), and thermal comfort in vehicles (ISO 14505: 1-4). There are also standards that support thermal comfort assessment such as for measuring instruments (ISO 7726), for subjective assessment methods (ISO 10551), and for estimation of metabolic heat production (ISO 8996) and clothing properties (ISO 9920).

Table 2. Recommended criteria for an acceptable moderate thermal environment as proposed in IS0 7730 (Olesen, 1995).

Parameter	Limits
General thermal comfort	
Predicted mean vote	$-0.5 < PMV < +0.5$
Predicted percentage dissatisfied	$PPD < 10\%$
Local thermal discomfort	
Draught	$DR < 15\%$ ($PPD < 20\%$)
Vertical air temperature difference between head and feet	$\Delta t_{air} < 3$ K ($PPD < 5\%$)
Radiant temperature asymmetry	
From cold vertical surfaces (window, wall)	$\Delta t_{pr} < 10$ K ($PPD < 5\%$)
From warm horizontal surfaces (heated ceiling)	$\Delta t_{pr} < 5$ K ($PPD < 5\%$)
Floor surface temperature	$19°C < t_{floor} < 29°C$ ($PPD < 10\%$)

ASHRAE 55-2004 (Thermal Environmental Conditions for Human Occupancy), on the other hand, deals with thermal comfort in the indoor environment with requirements based on 80% overall acceptability (10% dissatisfaction from general thermal discomfort and another 10% dissatisfaction for local thermal discomfort) (Olesen and Brager, 2004). It includes the PMV-PPD method for determining acceptable operative temperature for general thermal comfort, additional requirements for humidity, air speed, local discomfort, and temperature variations with time. An alternative compliance method applicable to naturally-conditioned buildings was also added based on the adaptive model of thermal comfort.

F. Radiant Heating and Thermal Comfort

Since energy demand for heating and cooling is directly affected by the required level of thermal comfort, determining the relationship between thermal comfort and energy demand (operating costs) is of foremost importance both to define the benchmarks for energy service contracts and to calibrate the energy labelling according to European Directive 2002/92/CE (Corgnati et al., 2008). In recent years, there has been a growing interest in the evaluation of the energy demand for building heating and cooling (energy performance of buildings). Several studies have already proven that incorporating radiant heating systems in building design has the advantage of reducing energy consumption while still maintaining acceptable thermal comfort level. From this concept, subsequent studies were done on designing radiant heating systems based on environmental parameters relevant to thermal comfort. Researchers have developed either automated methods for designing radiant heating panels based on MRT (Kalisperis et al., 1990) or design strategies based on thermal comfort criteria (Ling and Deffenbaugh, 1990).

III. Thermal Climate/ HVAC Control

HVAC engineering is the profession most directly occupied in the practice of thermal comfort, i.e. evaluating and designing for thermal comfort (de Dear, 2004). To be able to do these, target criteria for relevant thermal environment parameters must be known together with the methods for their prediction (design stage) or measurement (commissioning and operation). Based on this premise, there is then a **need** to (i) **define key indoor thermal climatic parameters**, (ii) **quantify their influence on the occupants**, and (iii) **discern the influence of the buildings and HVAC systems on these parameters**. Despite the obvious importance of thermal comfort in the design of indoor environment, it has not been effectively integrated with decision support tools. In the earlier years, this could be attributed partly to the absence of modular and flexible architecture software that facilitates dynamic data transfer between energy performance, air flow, and thermal comfort modules (Kumar and Mahdavi, 1999). But recently, the influence of energy demand on the expected level of comfort and of system control strategies has been investigated by means of dynamic simulations (Corgnati et al., 2008). Analysis of the seasonal energy demand can lead to the implementation of different comfort targets as a function of availability and costs of energy resources.

Over the years, there has been a significant increase in human control over his “immediate” surroundings. The concept of an individually-controlled microenvironment (ICS) (Fanger, 2000; Watanabe et al., 2010) has shown potential to satisfy more occupants in a space compared to a total volume uniform environment typically used at present. The degree of this controllability has increased strongly due to recent availability of power-operated mechanical means for environmental control (Mahdavi and Kumar, 1996) and the use of advanced technologies such as multiple-sensor HVAC system (Lin et al., 2002) and wireless sensor networks (Wang et al., 2003). Integration of these developments in HVAC control can be promising to result in (i) **more inclusion of building occupants in the control loops (user-adaptive and user-interactive)**, (ii) **achieving demand-responsive electricity management in residential and commercial buildings (energy-saving)**, and (iii) **combining the "now-separate" building mechanical, electrical, security, safety and comfort systems into one efficient system**.

IV. Indoor Environmental Quality (IEQ)

In general, indoor environmental quality (IEQ) and its relationship with energy consumption can be analysed by focusing on the use of strategies for microclimatic control, i.e. HVAC control system and the occupants' use of space (Corgnati et al., 2008). In this case, heating systems should be designed in a way that the lowest permissible operative temperature can be obtained, at a given design outdoor temperature, for an occupant in the coldest position within the occupied zone (Olesen, 1983).

Fanger (2000) proposed several principles regarding the elements behind a new philosophy of excellence in terms of indoor air quality in the 21st century. These are (1) **better indoor air quality to increase productivity and decrease "sick building symptom" (SBS)**, (2) **avoiding unnecessary indoor air pollution sources should be avoided**, (3) **the air should be served cool and dry to the occupants**, and (4) **individual control of the thermal environment should be provided**.

VI. Conclusion and Vision

With all the advantages and benefits proven by numerous studies in the last 50 years, it can be concluded that radiant heating systems offer the best potential to integrate all the elements required for an optimal indoor environmental quality (IEQ). With the latest relevant technologies and an established scientific background on thermal comfort available, the challenge now is on the development of an adaptive and fast-response radiant (IR) heating system based on an optimal thermal comfort - energy saving control. This intelligent IR heating system can then be incorporated into a wide range of building applications that require efficiency in design and control system to provide occupants with the best indoor environment experience.

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APPENDIX

Appendix Table 1. ISO standards related to ergonomics of the thermal environment

Standard reference	Title
EN ISO 11399:2000	Ergonomics of the thermal environment - Principles and application of relevant International Standards (ISO 11399:1995)
EN ISO 10551:2001	Ergonomics of the thermal environment - Assessment of the influence of the thermal environment using subjective judgment scales (ISO 10551:1995)
EN ISO 12894:2001	Ergonomics of the thermal environment - Medical supervision of individuals exposed to extreme hot or cold environments (ISO 12894:2001)
EN ISO 13731:2001	Ergonomics of the thermal environment - Vocabulary and symbols (ISO 13731:2001)
EN ISO 7726:2001	Ergonomics of the thermal environment - Instruments for measuring physical quantities (ISO 7726:1998)
EN ISO 8996:2004	Ergonomics of the thermal environment - Determination of metabolic rate (ISO 8996:2004)
EN ISO 7933:2004	Ergonomics of the thermal environment - Analytical determination and interpretation of heat stress using calculation of the predicted heat strain (ISO 7933:2004)
EN ISO 15265:2004	Ergonomics of the thermal environment - Risk assessment strategy for the prevention of stress or discomfort in thermal working conditions (ISO 15265:2004)
EN ISO 7730:2005	Ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria (ISO 7730:2005)
EN ISO 14505-2:2006	Ergonomics of the thermal environment - Evaluation of thermal environments in vehicles - Part 2: Determination of equivalent temperature (ISO 14505-2:2006)
EN ISO 14505-3:2006	Ergonomics of the thermal environment - Evaluation of the thermal environment in vehicles - Part 3: Evaluation of thermal comfort using human subjects (ISO 14505-3:2006)
EN ISO 11079:2007	Ergonomics of the thermal environment - Determination and interpretation of cold stress when using required clothing insulation (IREQ) and local cooling effects (ISO 11079:2007)
EN 15251:2007	Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics
EN ISO 15743:2008	Ergonomics of the thermal environment - Cold workplaces - Risk assessment and management (ISO 15743:2008)
EN ISO 13732-1:2008	Ergonomics of the thermal environment - Methods for the assessment of human responses to contact with surfaces - Part 1: Hot surfaces (ISO 13732-1:2006)
EN ISO 13732-2:2008	Ergonomics of the thermal environment - Methods for the assessment of human responses to contact with surfaces - Part 2: Moderate temperature surfaces (ISO 13732-2:2005)
EN ISO 13732-3:2008	Ergonomics of the thermal environment - Methods for the assessment of human responses to contact with surfaces - Part 3: Cold surfaces (ISO 13732-3:2005)

Standard reference	Title
EN ISO 9920:2009	Ergonomics of the thermal environment - Estimation of thermal insulation and water vapour resistance of a clothing ensemble (ISO 9920:2007, Corrected version 2008-11-01)
EN ISO 14505-2:2006/AC:2009	Ergonomics of the thermal environment - Evaluation of thermal environments in vehicles - Part 2: Determination of equivalent temperature (ISO 14505-2:2006/Cor 1:2007)

Appendix Table 2. ISO standards related to radiant heating

Project reference	Title	Directive	Current status	Foreseen date of availability
CEN/TC 130 - Space heating appliances without integral heat sources				
EN 14037-1:2003	Ceiling mounted radiant panels supplied with water at temperature below 120 °C - Part 1: Technical specifications and requirements	89/106/EEC		
EN 14037-2:2003	Ceiling mounted radiant panels supplied with water at temperature below 120 °C - Part 2: Test method for thermal output	89/106/EEC		
EN 14037-3:2003	Ceiling mounted radiant panels supplied with water at temperature below 120 °C - Part 3: Rating method and evaluation of radiant thermal output	89/106/EEC		
prEN 14037-2 rev	Free hanging heating and cooling surfaces for water with a temperature below 120°C - Part 2: Test method for thermal output of ceiling mounted radiant panels		Under Drafting	2013-08
prEN 14037-3 rev	Free hanging heating and cooling surfaces for water with a temperature below 120°C - Part 3: Rating method and evaluation of radiant thermal output		Under Drafting	2013-08
prEN 14037-4	Free hanging heating and cooling surfaces for water with a temperature below 120°C - Part 4: Test method for cooling capacity of ceiling mounted radiant panels		Under Drafting	2013-07
CEN/TC 228 - Heating systems in buildings				
FprEN 15316-4-8	Heating systems in buildings - Method for calculation of system energy requirements and system efficiencies - Part 4-8: Space heating generation systems, air heating and overhead radiant heating systems	No	Under Approval	2011-03
CEN/TC 180 - Decentralized gas heating				
EN 13410:2001	Gas-fired overhead radiant heaters - Ventilation requirements for non-domestic premises			
EN 419-1:2009	Non-domestic gas-fired overhead luminous radiant heaters - Part 1: Safety			
EN 416-1:2009	Single burner gas-fired overhead radiant tube heaters for non-domestic use - Part 1: Safety			

Project reference	Title	Directive	Current status	Foreseen date of availability
EN 777-1:2009	Multi-burner gas-fired overhead radiant tube heater systems for non-domestic use - Part 1: System D - Safety			
EN 777-2:2009	Multi-burner gas-fired overhead radiant tube heater systems for non-domestic use - Part 2: System E - Safety			
EN 777-3:2009	Multi-burner gas-fired overhead radiant tube heater systems for non domestic use - Part 3: System F - Safety			
EN 777-4:2009	Multi-burner gas-fired overhead radiant tube heater systems for non-domestic use - Part 4: System H - Safety			
EN 416-2:2006	Single burner gas-fired overhead radiant tube heaters for non-domestic use - Part 2: Rational use of energy			
EN 419-2:2006	Non-domestic gas-fired overhead luminous radiant heaters - Part 2: Rational use of energy			
EN 13410:2001/AC:2002	Gas-fired overhead radiant heaters - Ventilation requirements for non-domestic premises			

Appendix Table 3. Overview of related literature

A. RADIANT HEATING

REFERENCE	DESCRIPTION/ OBJECTIVES	APPROACH	CONDITIONS/ APPLICATION	MAJOR FINDINGS
Zhang and Pate (1989)	Design of heating panels with embedded tubes	Calculate over-all heating output as a function of several factors	Low-intensity heat sources (hydronic radiant ceiling panels) with well-insulated backside	The new method provided alternate approach for: - estimating heat output from a heating panel - establishing correlation between parameters involved in heating panel design that can be incorporated in computer simulations
DeWerth and Loria (1989)	Comparison of residential energy consumption and performance among in-space heaters and centralised heating (air furnace)	Installation of 4 types of in-space heaters (radiative or convective; vented or unvented) in 2 types of homes (1950's house and a modern, energy-efficient house) during winter period	In-space heaters • supplemental and sole source • radiative- or convective-type	In-space heaters used less electrical energy than central system (58% less in a 1950's house and 86% less in a modern, energy-efficient house).
Chyu (1989)	Understanding the breakdown mechanism of a cylindrical electric heater with a generally limited service life	Studying the uneven heating behavior of the heater through surface temperature variation measurement	Cylindrical electric heater	Non-uniformity of the surface temperature profile and eventual heater breakdown: • caused by uneven internal heat generation • increases with the number of heating-cooling cycles
Howell and Suryanarayana (1990)	Development of a procedure to relate panel heating surface temperature and area to the space heating requirements for room while maintaining Fanger's comfort constraints	Calculation of: • required area of radiant heater surface • radiant design heat loss and comparison to ASHRAE standard design procedure	Radiant heat ceiling panels	• Air infiltration rate has a significant effect on sizing of radiant panel heating units. • A radiant heating unit can be reduced in size by 4% at 1 ach, 9.5% at 2 ach, and 16% at 4 ach.
Kilkis et al. (1995)	Development of an analytical heat diffusion model and compare with finite-element (FE) solutions and standard DIN 1990	Calculation of heat output for an in-slab panel and a panel composed of layers with different thermal conductivities	In-slab (hydronic) floor-heating panels	The algorithm provided close agreement with respect to the required mean water temperature, thermal efficiency and heat output efficiency whilst the FE and DIN methods either overpredicted or underpredicted the parameters.

REFERENCE	DESCRIPTION/ OBJECTIVES	APPROACH	CONDITIONS/ APPLICATION	MAJOR FINDINGS
Kochendorfer (1996)	Overview of standardised testing methods for evaluating cooling output of room cooling panels	Discussion of problems encountered when transferring results from the lab to system design	Hydronic cooling panels	The conventional system in designing cooling panels (based on conventional air-conditioning system with convective cooling load extraction) can not be used for optimized design and planning.
Scheatzle (1996)	Development of an environmental control system in a desert-climate home based on combined radiative-convective system	• Control system developed based on operative temperature • Sensors monitored surface and ambient air temperatures and indoor humidity	Floor-ceiling radiant surfaces with hydronic source (convective-radiative hybrid)	The proposed system has potential to provide a more stable comfort at a lower operating cost.
Ardehali et al. (2005)	Proof-of-concept formulation/ procedure for modelling heat transfer mechanisms of radiant conditioning panels with considerations for the occupants of the thermal zone	• Literature review of key parameters affecting the performance of the conditioning panels • Development of a proof-of-concept model by analysing thermal performance of a conditioning panel	Conditioning panels at peak cooling during summer	• A higher panel surface temperature lowered the combined flux (radiative and convective) from the panel for a given ambient temperature. • The combined flux for the panel increased with increasing ambient temperature.
Dudkiewicz and Jezowiecki (2009)	Measurement of radiant thermal fields in industrial spaces served by high intensity radiant heater	Calculation of radiant temperature and asymmetry as functions of radiant heater position and indoor temperature	(Gas-fired) high temperature radiant heaters	• At a given point in space, radiant temperature and radiant temperature asymmetry can be affected by: - the distance from the envelope walls and from the radiant heater - indoor temperature • Highest radiant temperature asymmetry occur directly under the radiant heater • The longer the distance from the heater, the lower the temperature values • Radiant temperature is significantly correlated with radiant temperature asymmetry

B. THERMAL COMFORT

REFERENCE	DESCRIPTION/ OBJECTIVES	APPROACH	CONDITIONS/ APPLICATION	MAJOR FINDINGS
Schiller (1990)	• Determine the accuracy of theoretical and lab-based equations to predict thermal responses in office buildings • Examine the extent to which thermal comfort is associated with thermal neutrality	• Survey of workers' thermal assessment (ASHRAE Thermal Sensation Scale) and general comfort • Measurement of physical parameters (air temperature, dew point temperature, globe temperature, air velocity, radiant temperature asymmetry and illuminance)	10 office buildings, 304 subjects (1987 winter and summer in San Francisco Bay Area (US)	• The concept of comfort covers a broader range of thermal sensation than commonly assumed. • People voting within the extreme sensations are not necessarily dissatisfied. • Discomfort is more associated with extreme sense of warmth than coolness.
Jones and Ogawa (1992)	Development of a methodology on how to simulate the transient response of people to their environments, to changes in clothing and activity	Combination of the modified version of the two-node model by Gagge et al. (1971) with a recently developed transient clothing model by Jones (1991)	Transient conditions	There was a large difference in the distribution of heat flows (body and environment) between evaporative (sweating skin) and dry components (dry skin).
Olesen (1995)	Present standards for : • evaluating methods for moderate, hot and cold thermal environments • measuring and determining relevant parameters • measuring and evaluating individual physiological conditions of occupants	Comprehensive review and overview (tables) of the standards		Global standards provide a means to: • assess and design HVAC systems • Estimate optimal combination of environmental factors that will provide acceptable thermal comfort

REFERENCE	DESCRIPTION/ OBJECTIVES	APPROACH	CONDITIONS/ APPLICATION	MAJOR FINDINGS
Fanger and Toftum (2002)	Extension of the PMV (adaptive) model to include expectancy factor	Data from thermal comfort field studies in 4 cities (Bangkok, Brisbane, Athens and Singapore) were used to re-assess thermal comfort using the extended PMV model	Non-air conditioned buildings in warm climates	• Thermal sensation by occupants may have been predicted by PMV as severe than actual sensation due to overestimation of metabolic rate under warm conditions. • Occupants with low expectations were ready to accept warmer indoor environment which agreed well with observations behind the adaptive model.
Olesen and Parsons (2002)	Provide an introduction to ISO standards and proposed revisions concerned with thermal comfort assessment	Discuss the validity, reliability and usability of these standards		More studies are required to predict the combined influence of thermal environment on its occupants in terms of the effect of combined general and local thermal discomfort.
Jones (2002)	Explore the factors to consider in using thermal models of the human body and body-environment interactions	Some models were used as examples for discussion		A model is no better than the inputs to the model thus users of a standard must define these inputs accurately.
Olesen and Brager (2004)	Provide an overview of the key features and applicability limits of ASHRAE Standard 55-2004	In-depth discussion of each section in the standard		Occupants should be provided with personal control of their environment to compensate for inter- and intra- individual differences in preference
De Dear (2004)	Discuss methodological benefits and constraints of conventional climate chamber research in comparison to the field-based alternative	Analysis of issues such as sample size, demographics, research design, instrumentation and indoor climatic measurements, questionnaires, clothing insulation and metabolic rate assessment		• Design or operational criteria can be defined in PMV-PPD terms based on climate chamber research while field validation studies also support the use of this model only for centrally-controlled buildings. • In naturally-ventilated buildings, the architectural approach and related adaptive comfort standard is more useful.
Alfano et al. (2005)	Development of a user-interactive program to assess thermal environment (Thermal Environment Evaluation)	Use of numeric procedures incorporating relevant ISO standards	Assessment of thermal environment	Use of this software can provide a very easy assessment of thermal environment for both specialists and beginners in environmental ergonomics and building designers.

REFERENCE	DESCRIPTION/ OBJECTIVES	APPROACH	CONDITIONS/ APPLICATION	MAJOR FINDINGS
Linden et al. (2006)	New guidelines for thermal comfort based on adaptive thermal comfort model	Relevant literature research and temperature simulation calculations	Commercial buildings in The Netherlands	Evaluation tools for building designer, consultants and customers (e.g. questionnaires and measurement protocols) were made available in an online database.
Parsons (2006)	Heat stress Standard ISO 7243 based on wet-bulb globe temperature (WBGT) index	Detailed discussion of : • the standard in relation to human thermal environment, metabolic rate, clothing, and heat stress estimation • its applications, validity, reliability and usability	Thermal comfort assessment in hot environments	Estimates of metabolic rate are subject to error and adjustments have to be made based on the type of person and context of application.
Paulke and Wagner (2007)	• Review of the application of the finite element theory on the framework of formulas representing the thermoregulatory human system • Develop a simple-to-use method to assess local thermal comfort	Use of simulated skin and cloth temperatures and 'equivalent temperature' theory	Thermal manikin studies in vehicle simulation	Proper simulations of thermal neutrality in thermal manikins are required prior to thermal comfort conditions.
Conceicao and Lucio (2008)	Thermal study of a school building with real occupation levels in winter	Use of a software based on energy and mass balance integral equations to evaluate air quality and simulate thermal response of buildings	Buildings with complex topology (e.g. 3 levels, 97 compartments, 1277 main bodies, 211 transparent glass windows) in steady-state and transient conditions	The differences between numerical and experimental air temperatures and RH were <2 °C and 10-20%, respectively.
Corgnati et al. (2008)	Analysis of the relation between indoor thermal comfort conditions and energy demand for both heating and cooling	Validation tests based on de Dear's adaptive comfort theory	Heating and cooling in office buildings	• PMV fluctuations can be reduced by adopting a zone control of the HVAC system based on the operative temperature instead or air temperature • Adopting the adaptive comfort model into indoor operative temperature settings can reduce energy demand 50% with 10% PPD

REFERENCE	DESCRIPTION/ OBJECTIVES	APPROACH	CONDITIONS/ APPLICATION	MAJOR FINDINGS
Van Hoof (2008)	Assessment of thermal comfort using PMV model of Fanger and the concept of thermoneutrality vs. preferred thermal sensation	Discussion of the strengths and limitations of Fanger's PMV model in the 21st century		• Thermal neutrality is not always necessarily the ideal condition. • Very high/ very low PMV values do not necessarily reflect discomfort.
Orosa (2009)	Review of the principal local thermal comfort models and the implementation of its conditions	Discussion of each parameter in localised zones of indoor environment in relation to thermal comfort (PPD)		• Energy saving is possible if the number of air changes (ach), temperature and relative humidity are lowered to maintain the same PPD value. • A new control system based on local thermal comfort is possible in the future.
Peeters et al. (2009)	Development of comfort scales for building energy simulation based on comfortable temperature levels in the room	Recent reviews and adaptations were considered to extract acceptable temperature ranges and temperature scales	Thermal comfort assessment in residential buildings	Thermal comfort in residential buildings showed strong dependency on recent outdoor temperatures (weather data).
Karjalainen (2009)	Evaluation of thermal comfort in relation to the use of thermostats in homes and office rooms	Use of quantitative survey with a nationally representative sample in Finland based on the adaptive thermal comfort approach	Finish homes and offices	Thermal comfort levels were lower in offices than in homes due to lower adaptive control opportunities.
Yau and Chew (2009)	Thermal comfort study in 4 Malaysian hospitals	Field survey to investigate the temperature range for thermal comfort in hospitals	Thermal comfort assessment of buildings in the tropics.	• Only 44% of the hospitals met the comfort criteria specified in ASHRAE Standard 55 • Neutral temperature was 26.4°C and comfort temperature (for 90% of satisfied occupants) ranged from 25.3 to 28.2°C
Lee et al. (2010)	Evaluation of the advantages and limitations of 9-points categorical scale (CS), visual analog scale (VAS), and combined scale (graphic CS)	Use of questionnaire survey and controlled experiments	Subjective thermal comfort assessment	Graphic CS seemed more valid and sensitive for the measurement of thermal sensation but methodological and conceptual issues should be carefully considered before using this type of subjective thermal response evaluation.

C. THERMAL COMFORT AND RADIANT HEATING/ COOLING

REFERENCE	DESCRIPTION/ OBJECTIVES	APPROACH	CONDITIONS/ APPLICATION	MAJOR FINDINGS
Fanger et al. (1980)	Determination of the limits of overhead radiation to which man in thermal neutrality can be exposed without feeling discomfort	Climate chamber tests with human subjects and thermal manikin	Climate chamber (4.7 m x 6.0 m x 2.4 m) with a suspended ceiling made up of plywood (10 mm) and Rockwool (25 mm) insulation, underneath was an electrically-heated plastic foil painted to 0.95 emmittance	• Increasing overhead radiation increased skin temperature at the head region while decreasing skin temperature at the foot region which caused local thermal discomfort both for the head and foot region • 5% feeling discomfort (PPD < 5% = radiant temperature asymmetry of 4 K) should be the criteria for design of spaces with heated ceilings • Preferred mean skin temperature independent of radiation intensity from ceiling • Increasing radiation intensity should be compensated by lower air temperature to maintain constant operative temperature and comfort
Hart (1981)	Analytical study on the dependence of operative temperature on outdoor temperature	Use of 3 different types of heating systems: baseboard convection, all-air and radiant panel	Baseline case for office buildings: 4.6 m x 4.6 m x 2.7 m (L x W x H) with 2.1 m double-glazed window wall at one side	• Raising the air space temperature to a slightly higher value can maintain a constant operative temperature. • As outdoor temperature decreases, operative temperature also decreases.
Berglund et al. (1982)	Determination of occupant acceptance of radiation heated system for intermittent occupancy and the applicability of operative temperature control	Use of 5 operating modes to represent 5 reasonable ways of providing comfort to occupants who intermittently occupy a heated space during winter	Climate chamber (2.4 m x 2.4 m x 2.4 m) with high-intensity spot radiant heaters or 4 low temperature radiant ceiling panels (1.2 m x 1.2 m)	Operative-temperature controller was superior to air-temperature thermostat for controlling transient radiant heating systems because of: - Fast response - Less operative temperature overshoot - Greater thermal acceptability by occupants - Less overheating of the head region - Reduced power consumption (by 10%)

REFERENCE	DESCRIPTION/ OBJECTIVES	APPROACH	CONDITIONS/ APPLICATION	MAJOR FINDINGS
Zmeureanu et al. (1988)	Comparison between thermal performance of a radiant heating system and a warm air system	• Simulate transient heat transfer processes occurring in a heated room using a detailed computer program • Estimation of thermal comfort based on Fanger's PMV model	6.0 m x 6.0 m x 3.6 m room with one exterior wall at the intermediate level of an office building in Montreal, Canada on a cold, cloudy day (December 1979)	• For a given level of thermal comfort, radiant heating is more economical than the warm air system. • Peak load of radiant heating system was 38% lower than conventional systems.
Kalisperis et al. (1990)	Method to design radiant heating systems based on accepted comfort criteria and MRT	The required design space air temperature and proper sizing of panels were determined at the coldest point in the room to ensure constant, optimal comfort conditions	Can be applied to the design of conventional convective systems, hot water panel systems, and electric panel systems	By designing at a lower design air space temperature, the new method substantially reduced radiant panel size than those used in conventional methods.
Ling and Deffenbaugh (1990)	Design of a program to evaluate factors used by a currently accepted design methodology for low-temperature radiant heating applications	Analysis of recommendations concerning optimal panel location and prediction of space-heating load	Different enclosure types representative of room designs in actual residential and light commercial applications	Energy consumption-wise, enclosures with high insulation levels and high air changes per hour (ach) will be the best applications for radiant heating system Optimal panel location is not always adjacent to outside walls rather it depends on the location of glazing on the exterior walls
Athienitis and Shou (1991)	Numerical simulation model of room temperature control based on operative temperature in a room with radiant heating ceiling	Use of Laplace transfer functions for buildings from detailed thermal models used for building thermal control studies and energy analysis	Climate chamber with steady-state conditions Electric radiant ceiling heating with on-off SCR (silicon-controlled rectifier) control	Response time of radiant ceiling heating was significantly lower based on operative temperature compared to that based on air temperature at the same level of thermal comfort
Simmonds (1996)	Design criteria and route taken in designing energy-efficient systems for modern buildings in America	Use of PMV as design parameter	Hydronic radiant heating systems	MRT has a large influence on results of comfort analysis thus application of radiant heating proved an optimal solution to conditioning space within comfort limits (PMV ± +0.5)
Freestone and Worek (1996)	Numerical analysis of perimeter heating in a room by a radiant ceiling panel supplementing a central air-heating system	Investigation of the relation of radiant panel performance to thermal comfort and overall energy use	Radiant perimeter heating systems supplementing central air heating systems in multi-story buildings	The energy use can be lowered by removing the insulation from the top of the panel and placing a partition in the plenum to concentrate the heat in the perimeter area.

REFERENCE	DESCRIPTION/ OBJECTIVES	APPROACH	CONDITIONS/ APPLICATION	MAJOR FINDINGS
Watson et al. (1998)	Case study on the seven-system analysis of thermal comfort and energy use for a fast-acting radiant heating system	Comparison of energy consumption using electric concealed heating panels, fast-acting, ceiling surface mounted radiant panels, baseboard heaters, forced air furnaces, standard air + high efficiency air + geothermal heat pumps, gas forced air high efficiency furnaces		Significantly lower retrofit installed and maintenance costs for fast-acting radiant panels
Imanari et al. (1999)	Comparison of radiant ceiling panel system and conventional air-conditioning system in terms of thermal comfort, energy consumption, and cost	Use of three-dimensional steady-state radiative heat transfer analysis	Meeting room (55 m^2 floor surface area and ceiling height of 2.7 m) with radiant ceiling panels covering 56% of the ceiling area	• Radiant ceiling panels create smaller vertical variation of air temperature while heating. • Volume of supplied air was reduced thus eliminating draught and allowing lower energy consumption for air transport.
Petras and Kalus (2000)	Study of energy conservation using IR heaters and its impact on the indoor environment	Review of recent studies on the operation of gas infrared heater in industrial buildings	Gas-fired IR heaters installed at workplaces in industrial buildings	IR heaters have advantages for energy saving, economy of operation and more environmental-friendly than convective heaters
Miriel et al. (2002)	Evaluate the heating and cooling performances of a water ceiling panel system in relation to thermal comfort Develop and validate a simulation model (TRNSYS)	Test campaign during 2 winters and one summer where a water ceiling panel system and a monitory data acquisition system were installed in the laboratory	• Test room (14 m^2) with low thermal inertia and a double-glazed window facing west • 4 water ceiling panels covered 63% of surface area	Use of water ceiling panel system allowed 10% reduction in energy consumption
Feng et al. (2006)	Analysis of initial investment, performance and energy conservation in radiant heating based on a real heating system design and simulation	Thermal load of test building was calculated by means of a developed method and results were compared with traditional calculation methods		Low power radiation equipment (46-60 kW) is suited for buildings 5-12 m high while high-power radiation heating equipment (150 – 600 kW) is suited for buildings 8 – 35 m high.

REFERENCE	DESCRIPTION/ OBJECTIVES	APPROACH	CONDITIONS/ APPLICATION	MAJOR FINDINGS
Ghaddar (2006)	Level of thermal comfort in an occupied space while optimising the position of a radiant stove space-heating unit	• Use of finite element 3D model to accurately determine view factors and validating the view factor model against analytical and published data • Fanger's model was used to estimate thermal comfort	Room heating using a radiant stove unit	• The values of MRT, PMV and PPD depended strongly on the position of the radiant stove heater with respect to the cold window and occupant location • Changing the stove position in the room can save 14% of heating energy while maintaining the same level of comfort
Sakoi et al. (2007)	Thermal comfort for the whole body and local areas, skin temperatures, and sensible heat losses in various asymmetric radiant fields created by radiation panels	• Human subject experiments were used to assess overall comfort sensation , local discomfort and skin temperatures • Thermal manikins were used to precisely measure the local sensible heat loss	Non-uniform thermal environments: - Air temperature: 25.5 to 30.5 °C - Radiation panel surface temperature: 11.5 to 44.5 °C - RH: 40 to 50% - Inlet air velocity: <0.05 m/s	• Local heat discomfort in the head area was dependent on both local skin temperature and local sensible heat loss. • An overall comfort sensation tended to decrease with an increase in the magnitude of environmental thermal non-uniformity.
Wang et al. (2009)	Provision of graphs generated by the Berkeley Thermal Comfort Model (BCM) to allow designers to directly determine the acceptable range of floor and ceiling surface temperatures as a function of air temperatures for a representative room geometry	• Acceptability was defined as the absence of whole-body discomfort • Use of BCM model to predict skin and core temperatures, thermal sensation and thermal comfort for the whole body as well as for 16 body parts: head, chest, back, pelvis, left and right upper arms, lower arms, hands, thighs, lower legs and feet	- Activity level : normal office work (1.2 met) - Air velocity: constant at 0.1 m/s - Humidity: 50% - Clothing insulation: 0.59 clo - Room dimensions ((L x W x H) : 8 m x 8 m x 2.8 m - Radiant heating type: hydronic systems using reclaimed heat	Depending on air temperature: • acceptable floor temperature range was 15 -40°C, wider than that specified in ASHRAE 55 and ISO 7730 (19-29°C). • Acceptable ceiling temperature range was 10-50°C, also wider than the standards (radiant asymmetry < 5 °C for a warm ceiling).

D. THERMAL COMFORT-BASED INDOOR THERMAL CLIMATE : DESIGN AND ITS CONTROL

REFERENCE	DESCRIPTION/ OBJECTIVES	APPROACH	SUBJECT/ APPLICATION	MAJOR FINDINGS
Olesen (1983)	Simplified calculative method to evaluate thermal indoor environment at the design stage (based on Nordic Guideline for Building Regulations)	Calculation of operative temperature, floor surface temperature and radiant temperature asymmetry and comparing them with existing limits for an acceptable thermal environment		The difference in the calculated values using the calculative method vs. the existing method: - operative temperatures: < 0.5 °C - radiant temperature asymmetry: < 0.5 °C
Federspiel and Asada (1992)	Development of a user-adaptable comfort controller	• Parameters were adjusted with respect to actual thermal sensation ratings of the occupant s • Stability of controller based on *a priori* information about the parameters used	HVAC control for systems using residential heat pump air conditioner and on-off or PID controller	The effect of parameter adaptation should first be assessed when applying the calculative method in on-off or PID controllers.
Mahdavi and Kumar (1996)	Examined the underlying premises of indoor climate control technologies and the HVAC industry as well the concept of "total environmental control"	Review of methods and terminology in thermal comfort science with the focus of predictability of occupants' environmental preferences		• Significant increase in human control over the ' immediate'surroundings • The degree of this controllability has increased sharply due to recent availability of power-operated mechanical means for environmental control.
Kumar and Mahdavi (1999)	Implementation of a knowledge-based expert system support to augment thermal comfort simulation engine using field studies data	• Combined analytic and case-based approach to describe efficiency of the thermal comfort module developed • Simultaneous evaluation of thermal and energy performance with thermal comfort using PMV		• Thermal comfort calculations can be integrated in a computer-aided architectural design environment just like any other performance simulation. • The module developed can play a major role in optimising energy use and enhancing thermal comfort in a building.

REFERENCE	DESCRIPTION/ OBJECTIVES	APPROACH	SUBJECT/ APPLICATION	MAJOR FINDINGS
Fanger (2000)	Principles and new research results that could be the basis of providing excellence in future indoor environments			• Better indoor air quality (IAQ) increases productivity and decreases "sick building syndrome"(SBS) • Unnecessary indoor pollution sources should be avoided • The air should be served cool and dry to the occupants • Individual control of thermal environment should be provided
Kumar and Mahdavi (2001)	Integrated simulation environment that allows multiple performance evaluation, e.g. thermal comfort analysis form a shared object model of building	Detailed thermal comfort analysis performed to determine the factors causing discrepancy between predicted and observed values from field studies worldwide		• The empirical thermal comfort analysis can be used in designing better thermal environments. • Discrepancy between observed thermal comfort levels (ASH) and predicted thermal comfort levels (PMV) which can be due to overestimation of PMV in naturally-ventilated buildings in the tropics
Lin et al. (2002)	Evaluation of developed multi-sensor single-actuator control of HVAC systems using PPD	Mathematical modelling of the building , HVAC system and controls to form as basis of computer simulations		• Multi-sensor control strategies were better than single-sensor strategy in terms of energy performance and comfort. • Energy-optimal strategy reduced energy consumption by 17% while reducing PPD from 30% to 24%. • Comfort-optimal strategy reduced energy consumption by 4% while reducing PPD from 30% to 20%.
Freire et al. (2008)	Thermal comfort optimisation while minimising energy consumption using a model predictive control scheme	Using control algorithms and for single-actuator system	Control of indoor thermal comfort in buildings equipped with HVAC systems	Control algorithms used can simultaneously promote thermal comfort and energy consumption reduction due to the ability of the PMV controller to adapt to individual parameters.

REFERENCE	DESCRIPTION/ OBJECTIVES	APPROACH	SUBJECT/ APPLICATION	MAJOR FINDINGS
Watanabe et al. (2010)	Identification of the separate and combined heating/ cooling effects of the Individual Control System (ICS) options for optimal design of those in practice already	Testing the ICS which included personalised ventilation and several heating/ cooling options: - Convection-heated chair - Under desk radiant heating panel - Floor radiant heating panel - Under desk air terminal device - Round, movable air terminal device Results of thermal manikin experiments compared to an existing subjective human response data		• Dissatisfaction were mostly caused by insufficient heating capacity and longer response time of radiant heating panels as well as improper control of ICS. • System components should have short response time and higher capacity to cope with large individual differences among occupants in terms of preferred thermal environment.

E. LATEST RELEVANT TECHNOLOGIES, MEASUREMENT TECHNIQUES AND INSTRUMENTS

REFERENCE	DESCRIPTION/ OBJECTIVES	APPROACH	SUBJECT/ APPLICATION	MAJOR FINDINGS
Wang et al. (2003)	Application of wireless sensor networks in building controls to reduce energy consumption	• Described capabilities of new sensor networks • Assessed applications that can increase quality of control and energy efficiency • Suggested opportunities for future development		Highly flexible location of sensors and increased sensing density would make improvements in the energy efficiency and building occupants' well-being
Korukcu and Kilic (2009)	Use of IR thermography to determine the instant and transient temperature distribution of all surfaces inside an automobile and investigation of thermal discomfort caused by these surfaces	• Comparison of surface temperatures recorded by IR camera with those recorded by thermocouples every 10 s	Temperature measurements or thermal comfort assessment in an automobile cabin	• Good agreement between values obtained from the IR camera and thermocouples • Infrared thermography was more convenient and faster than conventional temperature measurement methods • CFD studies and thermal comfort models with regards to thermophysical interactions between subjects and ambient space can be validated both for static and transient conditions • The use of 2 or 3 IR cameras simultaneously allows measurement of the entire instant temperature distribution