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Radiation exchange between persons and surfaces for building energy simulations

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ABSTRACT

Thermal radiation within buildings is a significant component of thermal comfort. Typically the methods applied for calculating view factors between a person and its building surfaces requires great computational time. This research developed a view factor calculation method suitable for building energy simulations. The method calculates view factors by numerical integration of projected area factor. Over time the projected area factor of a person has been simplified by geometrical shapes. These shapes were compared with more complex equations on precision and calculation time. The same was done for the resulting view factors, where the results were compared with view factors found by ray tracing. While geometrical simplifications of the human body gave the fastest calculations, the complex equations gave the most accurate results. Non-rectangular surfaces and obstacles were treated by comparing intersection points with the edges of the surface, making the method applicable to rooms with complex geometry. The method for calculating view factors is robust and applicable to building energy simulation tools. Calculation time can be long depending on the complexity of geometry, grid-size and the choice of method for the projected area factor, but view factor calculations are done only once for a whole year simulation.

1. Introduction

Thermal radiation accounts for a substantial part of thermal comfort, and knowledge on radiation is therefore vital when simulating thermal comfort in buildings. To comply with legislation, architects and engineers work to optimise the building design in order to obtain lower energy consumption. Thermal comfort is often ensured by constraining variations in operative temperature in the energy optimisation process; but better measures would be predicted mean vote, PMV, or predicted percentage dissatisfied, PPD, and percentage dissatisfied, PD, calculated in a grid, to cover differences in the room. The overall goal is to be able to optimise the thermal comfort of the occupants in parallel with the buildings' energy consumption and the major objective is to describe a method for calculating view factors between persons and surfaces in a room for use in calculations of mean radiant temperature and radiant asymmetry.

By improving the calculation of thermal comfort in building energy simulation programmes, it is possible to see the consequences on the thermal comfort when changing the building design, not just as an average in a room but on a number of different points, taking more aspects into consideration than the operative temperature. It is especially important in buildings with a complex geometry, where mean radiant temperature and radiant asymmetry varies in the room and an area-weighted mean of surface temperatures is far from accurate.

Global thermal comfort is calculated as the energy balance of the whole body, affected by 6 parameters: air temperature, mean radiant temperature, air velocity, relative humidity, clothing level and activity level [1]. Local thermal discomfort can be caused by draught, temperature gradients, asymmetric thermal radiation and cool/warm floors [2,3].

Previous work by the authors describe ways to improve the simulation of clothing level [4] and air velocity and draught risk [5] for use in building energy simulation tools.

The objective of this paper was to present a methodology for calculating thermal radiant impact on a person for better simulation of thermal comfort in building energy simulation tools. The method calculates view factors by integration of the projected area

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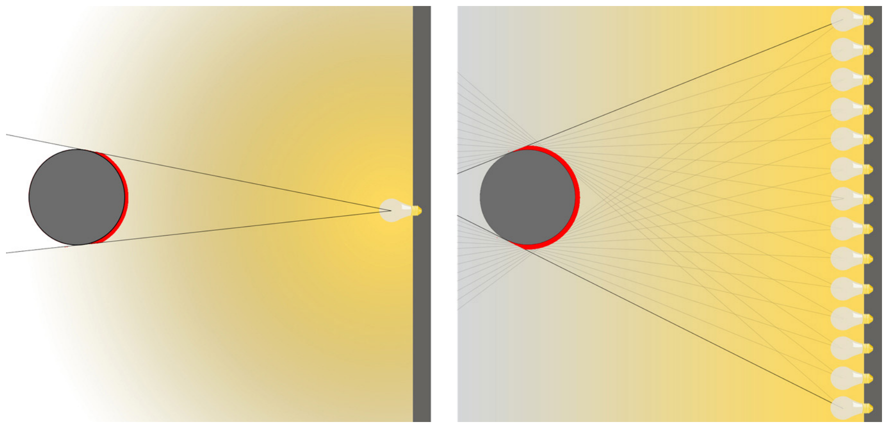

Fig. 1. To the left the projected area factor illustrated by the part of the body illuminated by a single light bulb. To the right the view factor to a wall illustrated by the part of the body illuminated by a wall of light bulbs.

factor over the surfaces and can be used for any plane surface, taking account of obstructions in the room. The method also applies for view factors for calculating radiant asymmetry. The same basic method is used for calculations between surfaces and between surfaces and a person.

For view factors involving a person, different methods and simplifications for calculating the projected area factor are compared, and the calculated view factors are compared with other methods. The comparison is made on both results and calculation time.

2. Theory

For the calculation of thermal comfort by using PMV or PPD and PD caused by radiant asymmetry, knowledge of the mean radiant temperature and radiant asymmetry are needed [1,3]. Mean radiant temperature is defined as that uniform temperature of a black enclosure which would result in the same heat loss by radiation as the actual enclosure under study. The definition covers both short wave radiation from the sun or a high-intensity radiant heater and long-wave radiation by emission from surfaces. This paper is focused on the latter while the impact on thermal comfort from short-wave radiation is treated by e.g. Karlsen [6]. Radiant asymmetry is defined as the difference in mean radiant temperature for each side of a small horizontal or vertical plate at the person's position in the room [7].

For comparing scenarios, the mean radiant temperature is an expression that is easier to relate to than a number of different temperatures of the surfaces.

The mean radiant temperature at a specific location is found by calculating the heat transfer through radiation in the actual enclosure. The radiant energy exchange between a person and a surrounding surface is calculated as between any two objects:

$$q_{1\to2} = \varepsilon \cdot \sigma_s \cdot F_{1\to2} \cdot A_1 \cdot (T_1^4 - T_2^4) = -q_{2\to1} \quad (1)$$

where $q_{1\to2}$ is the heat flow by radiation from object 1 to object 2 in W, ε is the multiple of the emissivities of the objects, $\sigma_s = 5.67 \cdot 10^{-8}$ W/m^2 K^4 is the Stefan–Boltzmann constant, $F_{1\to2}$ is the radiation view factor or angle factor from object 1 to object 2 (how big an area does object 2 cover compared with the whole area that object 1 radiates to), A_1 is the effective radiation area of object 1 in m^2, T_1 is the surface temperature of object 1 in K, T_2 is the surface temperature of object 2 in K, $q_{2\to1}$ is the heat flow by radiation from object 2 to object 1 in W.

Eq. (1) is only valid if reflection can be disregarded; which is only a reasonable assumption when the emission of the surfaces is close to the emission of a black body, where all radiation is absorbed and none is transmitted nor reflected. This is the case for many building materials and items of clothing, though glass is an exception as its emissivity can be very low, also for long-wave radiation.

To calculate the radiant exchange to a person, we need to know the surface temperature of the person and the surrounding surfaces, their areas, emissivities and the view factors between them.

The highest view factor is found when a surface surrounds a person, as the view factor of the surface is then equal to 1, as is the case for a sphere. The view factor is calculated from the projected area factor, and the projected area factor describes how much of an object is illuminated from a given point, as illustrated by the single light bulb in Fig. 1.

The view factor describes how much of the object is illuminated from a whole wall of light bulbs and can be found by integrating the projected area factor for each light bulb over the entire wall as illustrated to the right in Fig. 1.

For a person in a room, the sum of view factors to all surfaces equals 1.

The projected area of a person can be illustrated by his silhouette and depends on the view point to the person. The view point is described by the azimuth angle, α, and the altitude, β, as illustrated in Fig. 2.

The effective radiation area of a person is the area that emits and receives radiation from the surroundings. This area is smaller than the total skin area of the body, as parts of the body do not exchange radiation with the surroundings, e.g. between the toes or under the arms.

2.1. A historical view of view factors involving persons

Interest in the view factors between a person and surrounding surfaces arose in the late 1960s with HVAC systems and Fanger's studies on thermal comfort [1]. Before then, studies on thermal radiation to persons were mostly done to calculate the impact on persons from direct solar radiation, because the military needed knowledge about the effect of the sun on soldiers [8]. The first studies in the field were therefore not with the aim of describing view factors but merely the projected area factor of a person from different angles.

In the 1930s, James D. Hardy and Eugene F. DuBois used a wrapping method to determine the effective radiation area of a person. A person was wrapped in paper like an Egyptian mummy, and the surface area was measured by rubber-coating the paper, a technique similar to the one used to measure the total area of the human skin also known as the DuBois area. The effective radiation area was found to be 78.3% and 78.4% of the total skin area for the two persons they measured [9].