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Validation of periodic solution for computing CLTD (cooling load temperature difference) values for building walls and flat roofs

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ABSTRACT

In this study, periodic solution of unsteady heat transfer problem for building walls and flat roofs is firstly used to find the CLTD (cooling load temperature difference) values for these building elements. The solution is obtained by applying CFFT (complex finite fourier transform) technique. The solution of periodic nature is a novel approach in applying CFFT technique for calculating CLTD values for these elements. A computational procedure based on the periodic solution is developed, and a program in Matlab is prepared for the numerical calculations. The CLTD values are compared with those values given in ASHRAE handbooks. There is a considerable agreement between computed results and CLTD values provided in ASHRAE handbooks for the selected walls and roofs. It is obtained that differences in CLTD values for Roof 2, Roof 13 and Wall 3 selected for main directions change between 0 and 2.42 °C, 0 and 0.94 °C, and 1.8 and 4.3 °C, respectively. It is found that differences between estimated heat gain values and those given in ASHRAE by RTS (radiant time series) method change between 0 and 5 W/m^2. The numerical calculations are validated with ASHRAE standard data.

1. Introduction

Air conditioning is one of essential requisites for human beings, who need to live in spaces with comfort conditions all year round. The comfort conditions may be given as dry and wet bulb temperatures, humidity, air velocity and cleaning. It is necessary to cool the living spaces in summer season and to heat it in winter season. HVAC (heating, ventilating and air conditioning) system is employed for cooling the living spaces in summer season and heating in winter season. HVAC systems have been the most significant solution for a more comfortable life since long ago. Therefore, prediction of space cooling load is the central part of planning of building energy requirement or capacity of the HVAC systems. Transference of heat through building structural components is of paramount importance while estimating the space heating and cooling loads along with the energy requirement of any building [1]. In order to predict amount of energy consumption by HVAC system required precisely, it is imperative to apply transient thermodynamic method of analysis for heat flow estimations in building constructions. This is because the commonly used building blocks of buildings such as brick, concrete, sand, tiles are rarely in steady state. Due to adopting transient thermodynamic phenomenon apart from the computational expense, a significant complexity is imposed to the energy analysis of building and the dynamic simulation method of HVAC systems [2,3]. Especially, building envelops or exterior walls and roofs have an important role in decreasing or increasing heat loss and heat gain from these structures. The rate at which energy is transferred into or internally generated within any space at any instant is termed as heat gain. The heat gain of a building may consist of any one or all from following components: a) conduction of heat through exterior walls, ceilings and floors b) solar radiation through windows, ventilation or transparent surfaces, c) internal heat generated in the space by occupants, lights and appliances etc. d) atmospheric air ventilation and infiltration and miscellaneous heat gains [4].

Estimating the heat gain of a building accurately is prerequisite for the calculation of total cooling load and only on that basis the power rating of different components of air conditioning systems is decided. The heat gain through external opaque building elements comprises of a major part of cooling load and energy requirements in most of the buildings [5–8]. Hence, it is necessity to accurately estimate cooling load required as compensation for heat gained through exterior walls and roof. However the thermal storage effects of building structural components coupled with constantly

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changing external conditions make the heat gain phenomenon highly transient, subsequently making the process of having an accurate idea of the heat gain through external walls and roof complex and time consuming [5]. There are various different methods developed for calculation of heat gain by using solution of unsteady heat flow problem for the building envelope i.e. exterior walls and roof. These solution methods can be arranged in groups as exact and numerical solution techniques. The exact solution is the realistic solution, but it is very difficult to find temperature distribution in the building elements. Different exact and numerical solution methods are presented in literature. Recently, Bansal et al. [5] developed a unsteady heat flow in one-dimensional based model to evaluate the CLTD values for buildings' exterior walls and flat roofs. Celestino et al. [9] also developed a model using unsteady heat flow phenomenon and its corresponding numerical tool to predict the thermal behavior of multilayered walls and flat roofs. Barrios et al. [10] studied heat gain pattern of an intermittent air-conditioned room varying the shape of its outside walls and roofs and estimated its heat gain. There are some basic calculation methods with exact and numerical solutions which have been widely accepted with passage of time for the estimation cooling loads on the buildings. These are TFM (transfer function), CLTD (cooling load temperature difference), TETD (total equivalent temperature difference) and the RTS (radiant time series) methods. Calculation procedures for the TFM, CLTD and TETD methods are present in detail in refs. [2,11–13]. The TFM adopted by ASHRAE [11] is considered to be one of the most accurate methods for calculating heating and cooling loads. It is a widely used computer aided cooling load calculation method in air conditioning industry, and it uses a set of construction types with recalculated conduction transfer functions coefficients. These coefficients are tabulated for certain types of walls, partitions roofs, floors, and ceilings in ASHRAE [11]. Accuracy of cooling load calculations by using TFM depends on accuracy of transfer function coefficients [5]. Therefore, the coefficients should be computed accurately to obtain accurate cooling load for any structure. The CLTD is another cooling load calculation method which is a peak load calculation method that has been succinctly compiled by Spitler, McQuiston, and Lindsey [2]. The CLTD method is used with the CLTD values generated by utilizing the TFM or heat balance method for particular walls and roofs [5]. Thus the CLTD method is much simpler than the TFM method and is also very widely used for manual calculation and estimation of building cooling loads [5]. The accuracy of the CLTD method once again depends on the transfer function coefficients. It is also possible to generate the CLTD values for representative walls and roof using the heat balance method, and by solving transient heat transfer problem with appropriate initial and boundary conditions using a suitable numerical method. The TETD method is one of the first methods developed to account for transient effect of solar energy and thermal storage [14]. The solar energy affects interior environment and energy requirements of buildings. A fraction of the incident solar flux is collected and stored in the structural thermal mass of the building envelope, and influences essentially dynamic thermal characteristics of the building and the indoor environment especially during the cooling season. The RTS method is a simplified method for performing design cooling load calculations that is derived from the heat balance method. It effectively replaces all other simplified (non-heat-balance) methods, such as the TFM, CLTD/CLF and TETD/TA methods [19]. The RTS method is suitable for peak design load calculations, but it should not be used for annual energy simulations because of its inherent limiting assumptions. Besides this limitation it involves too many calculations to be used practically as a manual method [19].

Estimating heat gain from building walls and roofs worldwide with methods used for any certain region is not very exact. It is known that a procedure for CLTD values for building exterior structures established on transfer functions has been developed by ASHRAE for a typical place of 40° N on July 21 and for typical building exterior structures in North America with fixed interior and exterior situations [2]. For example, the CLTD values for proper building elements are tabulated for limited types of wall or inner partition, floor and roof or ceiling in ASHRAE [13]. However, there are no CLTD values for the other regions of the world and the other types of structures than the presented ones in ASHRAE [13]. The structures used in any regions and climatic conditions cannot be similar to those given in ASHRAE [13]. The CLTD values in ASHRAE are being used for similar structures, and the used CLTDs are corrected for any local region in the world. But the same structures to be calculated and their CLTD values cannot be found in ASHRAE. Therefore, analytical methods which eliminate the need of using tables should be developed to find CLTD values for any type of building elements with all types of exterior thermal conditions so that it gives an exact idea of cooling load for any regions in the world.

This paper is distinctive in the sense that for the first time CFFT technique is applied for the calculation of CLTD values for building envelope i.e. exterior structures. A computation procedure for the CLTD values for building exterior walls and roofs was developed. The procedure was based on periodic solution of unsteady heat flow problem for building exterior structures. The solution was obtained by applying CFFT technique for the problem formulation. Finding exact solution for the given thermo-physical properties of wall and roof materials and climatic conditions is analytical in nature. In this solution, hourly values of surrounding air temperature and solar insolation were utilized as climatic conditions. A computer program in Matlab supported on the periodic solution of unsteady heat transfer problem was developed for numerical calculations. It was used to calculate data for solar insolation hourly on the exterior walls, distribution of temperature in the wall and roof, and CLTD values for the building elements. Some walls and flat roofs generally used in Gaziantep, Turkey were selected from the ASHRAE [13], and CLTD values of those structures were calculated. As a result, CLTD values obtained from the present study were compared with those given in ASHRAE [13], and differences between them were discussed.

2. Mathematical model for the CLTD

A mathematical model for finding CLTD values of building walls and its flat roofs is a novel approach in the present study. The model is consisted of three components; namely, finding result for unsteady heat flow phenomenon, estimation of solar intensity on building wall surfaces, and expressions for the CLTD. Methodology for finding the CLTD has been based on energy balance for the exterior walls and roofs. In this balance, it is required to find distribution of temperature hourly in any given wall or roof during design day. In ASHRAE [13] and literature, the surface temperatures of building components have been calculated by using different numerical and closed solution methods such as finite difference, finite element and closed solution. In this study, CFFT is used to solve the unsteady heat flow problem for multilayered buildings' structural components, which is a new technique applied for calculating the CLTD values. In this section, procedures of the mathematical model are given briefly, which are solution of the problem, computation of solar energy flux on the structures and the CLTD.

2.1. Periodic solution of unsteady heat flow problem

A procedure for periodic solution of unsteady heat flow problem for a composite building wall or flat roof is presented in this section. Schematic representation of the wall and roof is indicated in Fig. 1. The building structure comprises of N layers, and the *n*th layer of