ESTIMATION OF COOLING LOAD USING FUZZY SET THEORY

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ABSTRACT

This paper presents a methodology to compute cooling load in the presence of uncertainties in the weather conditions and imprecise information. Fuzzy set theory is used for the estimation of cooling load. Maximum and minimum temperature of the day, humidity and number of occupants are treated as fuzzy parameters to calculate cooling load using fuzzy arithmetic. This provides cooling load as fuzzy parameter. Then a method is proposed to defuzzify it based on the user requirements.

INTRODUCTION

In view of energy crisis, the proper estimation of cooling load for an air-conditioned space is of paramount importance. An over estimation of cooling load will enhance the capital as well as running cost, on the other hand an underestimation will yield in the discomfort of the occupants. However, the proper estimation of the cooling load is a complex task because of various uncertain parameters.

The environmental conditions cause major uncertainties apart from other factors such as number of occupants inside the room. To account for uncertainties, two types of theories have been popular: probability theory and fuzzy set theory. Probability theory is used when an event is precisely defined and adequate statistical data is available. Various parameters are tested as stochastic variables and it is assumed that uncertainty and precision are of random nature. But it is found that the meteorological phenomenon have another kind of uncertainty, referred to as fuzziness, due to imprecise or insufficient data and subjectivity of opinion or judgement. These sources of uncertainty are caused by vague definition rather than by chance. Fuzzy sets deal with membership or non-membership of an object in a set with imprecise boundaries.

In meteorology, vague information often arises for example, the sentence "today is cold." In this case, there is no exact definition about which degree of temperature is being considered as "cold". Therefore, it seems much reasonable to treat the cooling load determination from the point of fuzzy set theory as proposed by Zadeh [1]. Fuzzy set theory has been used to solve a number of engineering problems. Dhawan [2] used fuzzy set theory for the estimation of cooling load and selection of the photovoltaic array size in the photovoltaic air-conditioning system. The present work follows the same methodology for the estimation of cooling load, but proposes a method to design the system at a cooling load depending upon the user requirement.

ESTIMATION OF COOLING LOAD

The design of an air conditioning system requires corresponding load to be estimated with good accuracy. The load calculation needs the information about the outside weather conditions and the desired inside conditions. Thus evaluation of cooling load must embody influence of all the factors. A computer program has been made to evaluate all the factors influencing the cooling load, viz. environmental factors, occupancy, air velocity and electrical load of the room.

For the temperature variation during the day, a mathematical model [3], has been adopted which gives a close approximation to an average value equal to the mean daily temperature range. The final expression for outside temperature (T_0) as a function of time (t) comes out to be harmonic series of first order:

$$To = \frac{(T\max + T\min)}{2} + \frac{(T\max - T\min)}{2}\cos\{15(t - tsr + 1)\} \qquad (1)$$

where, T_{max} and T_{min} are the maximum and minimum temperature of the day and t_{sr} is the time of sunrise. It is assumed that minimum temperature in the days occurs one hour before sunrise and maximum temperature occurs 12 hours after that.

For the calculation of the heat transfer, it is convenient to combine the effects of the outside temperature and solar radiation into a single fictitious quantity called the sol-air temperature. The rate of heat transfer (q) from outside to inside surface of a sunlit structure is given as,

$$q = ho(To - Two) + a_t I_t \qquad (2)$$

where, h_0 is the convective heat transfer coefficient at outside surface, T_{wo} is the outer wall temperature; I_t is the rate of incident radiation and a_t is the absorptivity of the structure. The heat transfer can also be written as:

$$q = h_o(T_s - T_{w,o}) \qquad (3)$$

where T_s is the sole air temperature.

Comparing the equations (2) and (3), the sole-air temperature is obtained as,

$$T_s = T_o + \frac{a_t I_t}{h_o} \tag{4}$$

The outside air convection heat transfer coefficient, h_o is calculated from Kadambi and Hutchinson [4] as,

$$\begin{aligned} h_o &= 14.27 + 3.55\ V_0 && \text{for very smooth surface} \\ &= 18.42 + 3.81\ V_0 && \text{for smooth surface} \\ &= 26.55 + 5.06\ V_0 && \text{for rough surface} \\ &= 28.64 + 6.36\ V_0 && \text{for very rough surface} \end{aligned}$$

where V_0 is the outside velocity in km/hr and h_0 is in kW/m^{2}K

The field studies reveal that for hot and humid climates, the comfort conditions are about T_{db}=22 ^{0}C, RH = 55 %, V_i=0.8m/min.

Components of cooling load which are considered here as follows:

Heat transfer through walls and roofs

Heat transfer through walls and roofs is calculated by the method of time lag and decrement factor method [5]. Combined effect of outside air temperature and incident solar radiation intensity gets accounted, because sol-air temperature is used for all calculations. Thus, the structural heat load Q_{st} including solar radiation is found to be

$$Q = \sum Q_k = \sum \{(UA)k[(Tsk - Ti) + \lambda k(Tsk(-\tau) - Tsk)]\} \tag{5}$$

where, T_{sk} is the sol-air temperature on the k^{th} surface of the structure, λk is the corresponding decrement factor, τ is the time lag and UA is the product of overall heat transfer coefficient and surface area. $T_{sk(-\tau)}$ is the sol-air temperature at (t - τ) time.

If the walls and roofs have three layers of materials with thickness x_i and thermal conductivity k_i where i is the layer of structural material then U is given by the following expression:

$$U = \left(\frac{1}{\left(\frac{1}{h_o} + \sum \frac{x_i}{k_i} + \frac{1}{h_i} \right)} \right) \tag{6}$$

Heat transmission Through Glass Windows

Solar radiation, direct and diffuse, incident upon a glass surface is, in parts, transmitted, reflected and absorbed. Thus if τ, r and a represent the respective fractions known as transmissivity, reflectivity and absorptivity, then

$$\tau + r + a = 1 \tag{7}$$

The heat gain of the space through glass then comprises of

i) All the transmitted radiations.
ii) A part of the absorbed radiations that travels to the room.
iii) The heat transmitted due to the temperature difference between the outside and inside.

The direct radiation enters the space only if the glass is receiving the direct rays of the sun. The diffuse radiation enters the space even when the glass is not facing the sun.

The heat gain of the space is [5]

$$Q = (A_{sun}\tau_D I_D + A\tau_d I_d) + \frac{(A_{sun}a_D I_d + A a_d I_d)}{(1+\frac{h_o}{h_i})} + UA(t_o - t_i) \tag{8}$$

where subscript D and d denote direct and diffuse radiations, respectively, and U is the over all heat transfer coefficient given by

$$\frac{1}{U} = \frac{1}{h_i} + \frac{1}{h_o} \tag{9}$$

the values of transmittivity and absorptivity of glass are taken from Arora [5].

Infiltration Load

Infiltration is the leakage of outdoor air into a building through cracks openings caused by pressure difference across the boundary surfaces. The exchange of air may lead to both heat and moisture gain into the space. The volume of infiltration is related in terms of the room volume. It is tabulated by Prasad [6].

The expression for the infiltration load is

$$Q_{infil} = \frac{V_{room}N_A(h_{oa} - h_{ia})}{24v_{air}} \tag{10}$$

where V_{room} is the volume of the room, V_{air} is the specific volume of the air at outside temperature, N_A is the number of air changes/day, h_{oa} and h_{ia} are the enthalpies of outside and inside air respectively.

Ventilation Load

Ventilation air requirement is given in Prasad [6]. The procedure is same as calculating the infiltration load.

Internal Heat Load

It comprises of occupancy load, lighting load and appliances load. Occupancy load is calculated from values given in Arora[5]. Lighting and electrical appliances load is calculated by taking into account the total power consumption of lights and electrical equipment.

The total load for a room at a particular time is calculated by adding all the components of load at that time. By taking into account the hourly load, the system may be selected.

APPLICATION OF FUZZY SET THEORY

The main critical parameters are maximum and minimum temperature of the day, humidity, the number of occupants, [2] so these are taken as fuzzy. The parameters are characterized by their membership function. Membership function is taken as triangular (as shown in Fig. 1) for the sake of simplicity. Triangular membership function can be expressed as

$$\mu(x)=\begin{cases}0 & (x\le l'),\\ \dfrac{x-l'}{m-l'} & (l'\le x\le m),\\ \dfrac{h'-x}{h'-m} & (m\le x\le h'),\\ 0 & (x\le h')\end{cases} \qquad (11)$$

where,

$$l'=\begin{cases}m-2(m-1) & (m\ge 2(m\text{-}1)),\\ 0 & (m\le 2(m\text{-}1)),\end{cases} \qquad (12)$$

and $$h'=m+2(h-m) \qquad (13)$$

Here *l, m* and *h* are the expert estimates of the parameter for low, most likely and high values respectively. The values of μ is 0.5 at $x=l$ and $x=h$ and 1 at $x=m$. These fuzzy parameters lead to fuzzy arithmetic computation at each α-cut. In general, computations need to be carried out at a number of α-cuts. However, Akhauri and Meel [7] found that cooling load can be approximated as a triangular fuzzy number. Hence, the computation at the α-cut of 0.5 and 1 are sufficient to draw the possibility distribution of cooling load. Design parameters then are obtained as fuzzy numbers.

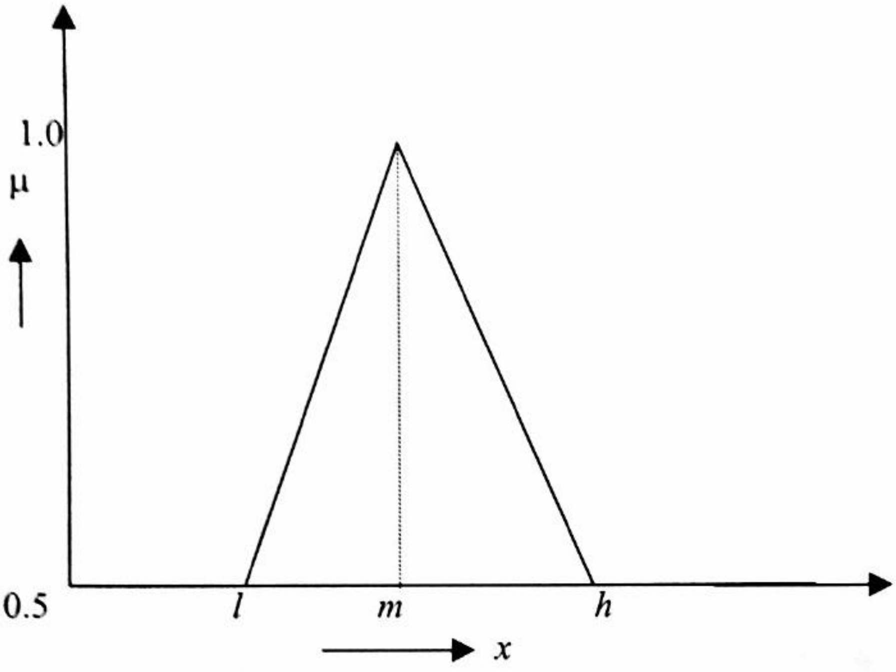

Fig. 1: A typical fuzzy number

SYSTEM RELIABILITY:

For calculating the reliability of airconditioning system based on a particular load we follow the procedure developed by Dixit and Dixit [8]. For fuzzy parameters we obtain cooling load as fuzzy output. Suppose we are interested to know the reliability at a crisp value of cooling load, *x*. Reliability depends on the two factors. The first one is possibility index (*PI*), which is defined as

$$PI(\mu, x) = \begin{cases} \dfrac{x - x_L(\mu)}{x_R(\mu) - x_L(\mu)} & \text{if } x < x_R(\mu) \\ 1 & \text{if } x \geq x_R(\mu) \end{cases} \qquad (14)$$

In the above equation $x_R(\mu)$ and $x_L(\mu)$ are the right and left hand limit of cooling load at the membership grade μ. Normally, *x* will be greater that its value at membership grade 1. Note that besides *x*, *PI* is also a function of μ. Therefore, there is a degree of uncertainty associated with each possibility index. A measure of this uncertainty can be defined using Shannon's function [9].

$$d(\mu) = -[\mu \ln \mu + (1-\mu)\ln(1-\mu)] \qquad (15)$$

Then $(1\text{-}d(\mu))$ can be considered as a measure of certainty. Now a reliability index can be defined as

$$\beta(\mu, x) = PI(\mu, x)[1 - d(\mu)] \qquad (16)$$

Note that for a design cooling load *x*, the index β also depends upon the membership grade μ, but the definition of the reliability should be independent of μ. To make it μ independent, we can take the area under the β-μ graph as the measure of the reliability. The maximum value of area corresponds to the case when $PI = 1$ for all μ. So it should be taken as 100 % reliability. Thus, the reliability can be defined as

$$\mathrm{Re} = \frac{\int_{0.5}^{1} \beta(\mu, x)\,d\mu}{\int_{0.5}^{1} (1 - d(\mu))\,d\mu} \times 100 \qquad (17)$$

A METHODOLOGY TO DEFUZZIFY THE COOLING LOAD

As a result of fuzzy computations, the cooling load is obtained as a fuzzy number. However, an airconditioning system designer needs the crisp value of the cooling load to base his design of various components. As mentioned in the previous section, different crisp values of cooling load will provide different reliabilities of the system. As the design cooling load increases, the reliability increases, but the cost also increases. Hence, a compromise has to be made.

Here, an example is taken to illustrate how fuzzy set theory can help in arriving at a compromise value. Specifications of the room selected for study are same as in [2]. Weather data of Guwahati was collected from Department of Metrology, Guwahati. Possibility distribution of cooling load in the month of June is shown in Fig. 2. The cooling load varies with time in a particular day. However, considering the amount of variation, a system designed on the basis of average load may be appropriate. Such a system can take some overload when required. The possibility distribution of average cooling load (based on inside design temperature of 22 ^{0}C) is shown in Fig. 3. Suppose one wants to know the performance of a system, designed on the basis of 4 kW cooling load. Its reliability for different inside design temperature may be found out by the procedure given in this paper. Table 1 shows the reliability for various inside design temperatures.

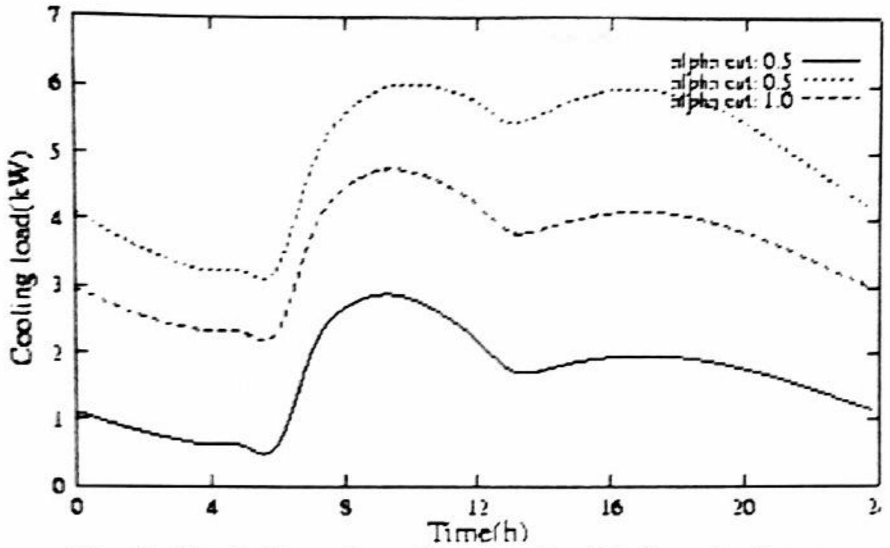

Fig. 2: Variation of cooling load with time in June

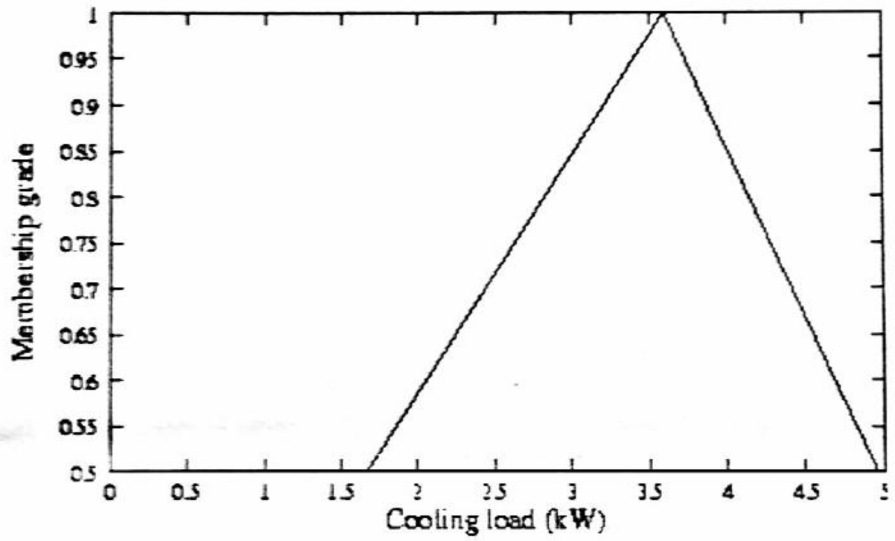

Fig. 3: Average cooling load for the month of June

Table1: Reliabilities of a system designed on the basis of 4kW for various inside design temperatures

Inside Design Temperature (^{0}C)	Reliability
22	95.7
23	99.1
24	99.9
25	100.0

Based on a study carried out by Singh [10], inside design temperature of 22 ^{0}C is an excellent design, hence a weight of 10 is assigned to it. Similarly, the weights of 8, 6 and 4 are assigned to designs providing the inside design temperatures of 23 ^{0}C, 24 ^{0}C, 25 ^{0}C respectively. Overall performance can be taken as the weighed average of reliabilities. Overall performance in the present case comes out to be

$$\text{Overall performance} = \frac{95.7\times10+99.1\times8+99.9\times6+100.0\times4}{10+8+6+4} = 98.186$$

In a similar way, one can obtain the performance of the designs based on other cooling loads also. Cost estimation for these designs may be carried out and a curve can be drawn between the cost and overall performance. This curve can help the user to indicate the suitable compromise value of cooling load based on his relative preferences for cost and reliability.

CONCLUSIONS

This paper presents a methodology for the proper estimation of cooling load based on the fuzzy set theory. A method for designing the system at an optimum cooling load is proposed. The methodology require fair amount of computation. In view of, the energy crisis, the computational effort is justified. Future work is directed towards developing more powerful methods for decision-making and validating the approach by field trials.

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