Eighth International IBPSA Conference
Eindhoven, Netherlands
August 11-14, 2003

MODELLING THERMAL COMFORT FOR TROPICS USING FUZZY LOGIC

Henry Feriadi, Wong Nyuk Hien
Department of Building, School of Design and Environment
National University of Singapore
4 Architecture Drive, Singapore 117566

ABSTRACT

Present international standard for thermal comfort such as ASHRAE Standard 55 and ISO 7730 were developed to serve as a guideline for moderate thermal environments e.g. mechanically air-conditioned spaces [CEN ISO 1995]. Recent thermal comfort studies had reported that some discrepancies were observed in its application for Naturally Ventilated (NV) buildings in hot and humid tropical climate [Feriadi et.al 2003]. The standard failed to take into considerations tolerance and different perception of thermal comfort from different environmental setting. In this study, fuzzy logic approach is used to model an appropriate Thermal Comfort (TC) standard for tropical naturally ventilated houses. The complexities of the human cognitive process and the vagueness of linguistic expression are considered. Fuzzy logic is used as a mathematical model to allow representation of human decision and evaluation processes in algorithmic form. A detail exposition of the application which combined the linguistic approach to the optimization under multiple thermal condition criteria is presented.

INTRODUCTION

Human thermal comfort is very difficult to model mathematically since the real process in human perception (justification over environmental condition) is still unknown and far too complex to comprehend. It can be considered that the human is a "black box" which receives inputs, the environmental and personal variables, and whose output is the subjective perception of thermal comfort (figure 1).

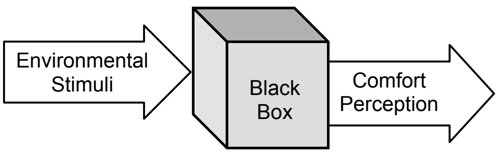

Figure 1: Black box process of human perception

The above process might be regarded also as a multi-objective optimisation problem on which each of the performance factors are influenced by many parameters. For example, high room temperature and humidity are known as detrimental factors for thermal comfort but people who live in tropics usually can compensate by wearing light clothing, and adjusting their level of activity. The actual process of human perception is remarkably complex and is also varied between people even though they experience the same environmental condition.

Some uncertainties have been identified in thermal comfort modelling. They include:

- **Lexical Uncertainty.**

  The uncertainty is due to the nature of language used (lexical uncertainty) in describing the individual environmental parameter. The uncertainty deals with the imprecision that is inherent in most words humans use to evaluate concept and derives conclusions [Kosko 1993]. For example, warm air temperature has no exact definitions in existence determines the threshold above which condition is conceived as warm.

- **Human Perception Uncertainty**

  This uncertainty deals with the nature of human thermal perception which is rather "black box" concept in evaluating thermal condition. For example, it is known that wind speed will enhance people's thermal comfort. However, what is the definition of windy or still wind, and how much will the increase in wind speed influence the thermal comfort when a person wearing t-shirt and short pant sits relax in a slightly cool environment? In real life, by using abstraction and by thinking analogies, a few sentences can describe complex contents that would be very hard to model with mathematical precision.

- **Subjective Scale uncertainty**

  The other inherent problem is the scale used for TC survey is not always linear quantitative in nature. The sensation of warm is not perceived as a double of slightly warm or hot is not always double sensation as warm. Previous thermal comfort modelling mainly considered the scale in a linear quantitative way which may not be the most appropriate way to analyse human response.

METHODOLOGY

To collect primary data which is required for thermal comfort modeling, comprehensive field survey had been carried out. By conducting survey in the actual living environment, it is expected that the dynamic interaction between occupant's perception and their NV environment can be realistically captured.

The total data of 538 samples from Singapore and 525 data from Indonesia were collected through some extensive field surveys during rainy and dry seasons in the year 2000-2002. The large sample size (a total of 1063 samples) has minimized the risk of bias that might occur in relatively smaller samples used for statistical analysis. For each survey, both objective and subjective measurements were carried out simultaneously. The purpose of objective measurement is to capture some personal and environmental parameters that are commonly used for thermal studies (Clothing, Metabolic rate, Dry Bulb Temperature/DBT, Mean Radiant Temperature/ MRT, Relative Humidity/RH, and Air Velocity/Vs).

Subjective measurement makes use of seven scales of thermal sensation (known as ASHRAE scale), and other relevant perception scales (such as airflow, humidity etc). The respondents were required to answer those questionnaires respectively, which reflected their relevant thermal sensation and perception.

The data obtained through the survey are analysed using appropriate statistical tools to find out the correlation between environmental stimuli (affecting thermal comfort) and people's perception. Each question in the questionnaire asks specifically about the present environmental stimulus such as:

- "*How do you feel at this moment?*"
  (related to the thermal sensation measured by DBT and MRT)
- *"How do you feel about room air humidity now?"*
  (related to the level of relative humidity - % RH)
- *"How do you feel about room airflow now?"*
  (related to the wind sensation – m/s)

The respondent need to answer those questions by choosing only one standardised answer (response) on seven scale votings (Table 1).

Table 1

	Environmental stimuli	**Sensation measured** (subjective vote - 7 scale)
1	Air temperature (^{0}C)	Thermal sensation
2	Radiant temperature (^{0}C)	Thermal sensation
3	Humidity (% - RH)	Perception of humidity
4	Wind speed (m/s)	Perception of airflow

DATA ANALYSIS

Human (individual) thermal comfort perception on a particular indoor thermal condition is always differed even though under the same environmental condition (room). It is impossible to design a thermally comfortable indoor environment which can satisfy all occupants all the time. Thus there is no precise description about thermal condition at which everyone perceives it as most comfortable temperature. In this perspective, it is understood that people's thermal comfort perception is greatly influenced by environmental conditions (stimuli) but their influences show rather "fuzzy" (imprecise) rather than precise relationship.

The analysis of thermal comfort perception can only implies the probability (likelihood) of people to perceive and vote according to particular thermal perception scales. For example, when air temperature increases into warmer condition, the probability of people perceive as 'comfortable' will decrease. On the other hand, when air temperature decreases into cooler conditions, the probability of people vote for 'comfortable' will also be lower.

One of the powerful statistical methods to analyse and predict the thermal comfort response is Probit regression analysis. This analysis is drawn originally from studies of threshold pesticide levels and insect kill rates. Probit analysis assumes that the likelihood of an event happening increases as the stimulus intensity increases [Finney 1962]. In the method used in this study the probability "p_i" of an event having happened in the " i " observation is defined according to the standard cumulative normal distribution function:

$$p_i = \int_{-\infty}^{\eta_i} \frac{1}{\sqrt{2\pi}} exp\left(-\frac{1}{2}u^2\right)du$$

The probit analysis is applied separately for four environmental stimuli which are believed to give impacts on thermal comfort perception (in Table 1). This analysis provides suitable method to calculate the proportion of probability to vote certain scale as the stimulus changes. The Probit analysis was performed using SPSS v10 ® statistical software and the results for the four environmental parameters are presented in the following figures:

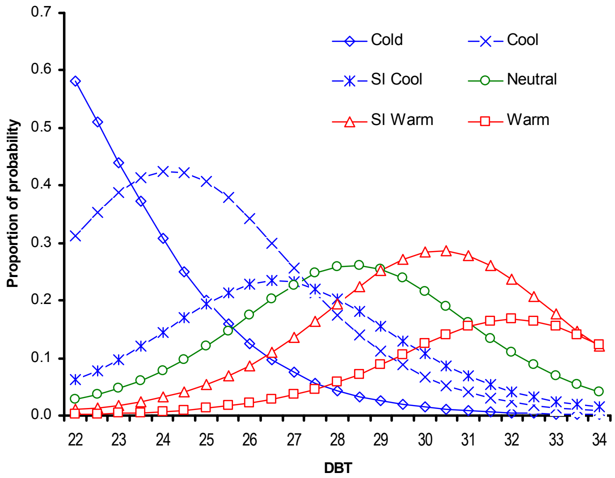

Figure 2: Probit curves for Dry Bulb Temperature

In general the Y-axis in probit curve shows the proportion of probability of response. The Y-axes values range between 0 to 1, with 0 means no (very low) probability and 1 means highest probability (certainty). The X-axis displays the scale of 'the stimuli'. In Figure 2, the X-axis represents stimuli of Dry Bulb Temperature (DBT) bin which the scale ranges from $22^0 – 34^0$ C.

The above figure shows that the highest proportion of probability (curve's peak point) for 'Neutral' response is found at 28.5^0 C. People are likely to perceive the condition as 'Cool' when air temperature reaches about 24^0 C. The response of 'Hot' is not analysed because of very low data captured from the field survey.

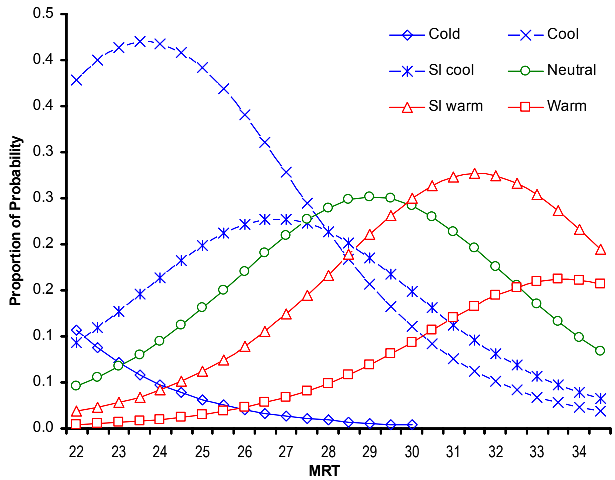

Figure 3: Probit curves for Mean Radiant Temperature

It is shown in Figure 3 that the maximum probability for 'Neutral' is located at 29^0 C of MRT. The high likelihood of people to perceive the condition as 'Warm' is found when MRT reaches about 33.5^0 C. Again here the vote (response) of 'Hot' was not further analysed because of insignificant number of data collected from the field survey. The curve for 'Cold' vote also shows very low probability (less than 0.1).

Comparing with DBT probit analysis results, the average results of MRT show only about 0.5^0 C higher. This is due to the absence of direct solar radiation since all field measurements were conducted in well shaded of indoor places (living rooms) and about half of the data were collected in the evening.

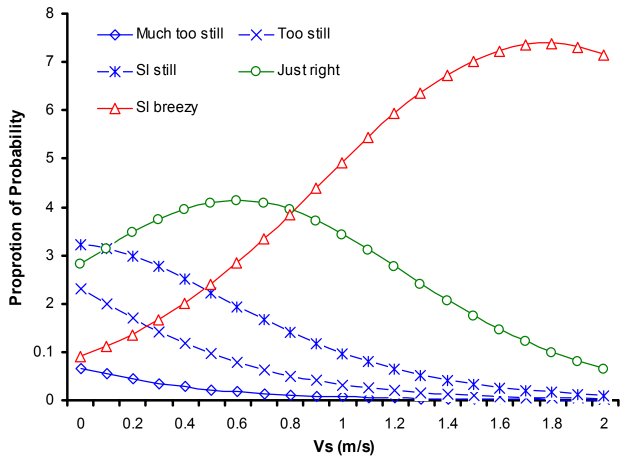

Figure 4: Probit curves for Wind speed

From the seven vote scales of airflow, only five scales are chosen for Probit analysis. The scales of 'Breezy' and 'Much too breezy' have a very low numbers to allow reliable statistical analysis. During field survey, wind speed were recorded within the range of 0 – 2 m/s, therefore people probably still perceive those wind speed within acceptable range and tend to consider the air flows as not 'Breezy' or 'Much too breezy'.

The maximum probability of air flow perception of 'Just right' is found at 0.6 m/s. Meanwhile the maximum likelihood of air flow perception for 'Slightly breezy' is found at 1.8 m/s. The Probit curves for other three scales (Slightly still, Too still and Much too still) were similar. Those peak curves (maximum points) only show differences on the proportion of probability. It implies that the wind speed below 0 - 0.6 m/s (below 'just right' wind), people have classified wind speed generally within various degree of still wind (stagnant).

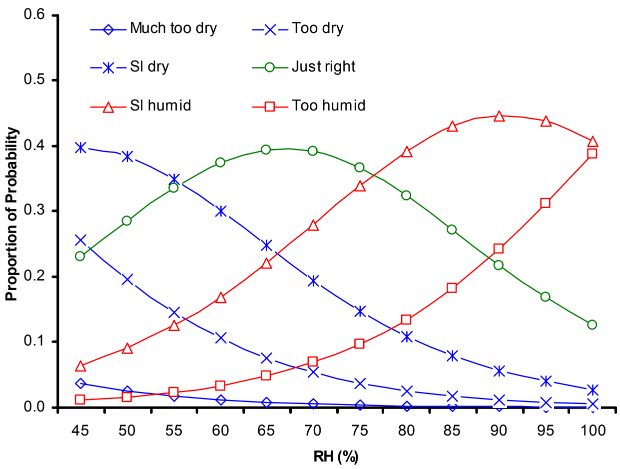

Figure 5: Probit curve for Relative Humidity (RH)

The Probit analyses were made within RH stimuli range of 45 – 100%. In Figure 5, the maximum probability of humidity perception of 'Just right' is found at 65% RH. Meanwhile the maximum likelihood of humidity perception for 'Slightly humid' is found at 90% RH. The Probit curves for other two scales (Slightly dry and Too dry) demonstrate the peak at 45% RH. The curve of 'Much too dry' is relatively flat in shape and always below 0.1 value of probability. It gives an indication that people are not likely to vote for this scale. Subsequently, there is also no vote for 'Much too humid' therefore the probit analysis is not performed.

It is necessary to inform here that probit analysis are only applied for four environmental parameters. The other two personal parameters (clothing, metabolic rate) are analysed separately based on the simple data distribution and mean analyses since the questionnaire do not ask people to vote clothing and metabolic rate.

MODELLING

The schematic diagram of conceptual modelling of thermal comfort perception using Fuzzy Logic is presented in Figure 6. First step in the modelling is called ***fuzzification***, which defines linguistic variables, term and membership functions. Originally the concept of linguistic variable was introduced by Zadeh, as an approach (mean) to capture natural expressions commonly used by human [Zadeh 1965].

The second step is called ***fuzzy rule inference*** whereby some sets of fuzzy logic operators and production rules are defined. The most common rule is called IF-THEN rule which can be used to formulate the conditional statements that comprise fuzzy logic.

The final step in modelling is ***defuzzification*** process. The input for the defuzzification process is a fuzzy set (the aggregate output fuzzy set) and the output is a single number. The aggregate of fuzzy set encompasses a range of output values, and so must be defuzzified in order to resolve a single output value from the set. The detail discussion about the modelling steps is presented in the following sections.

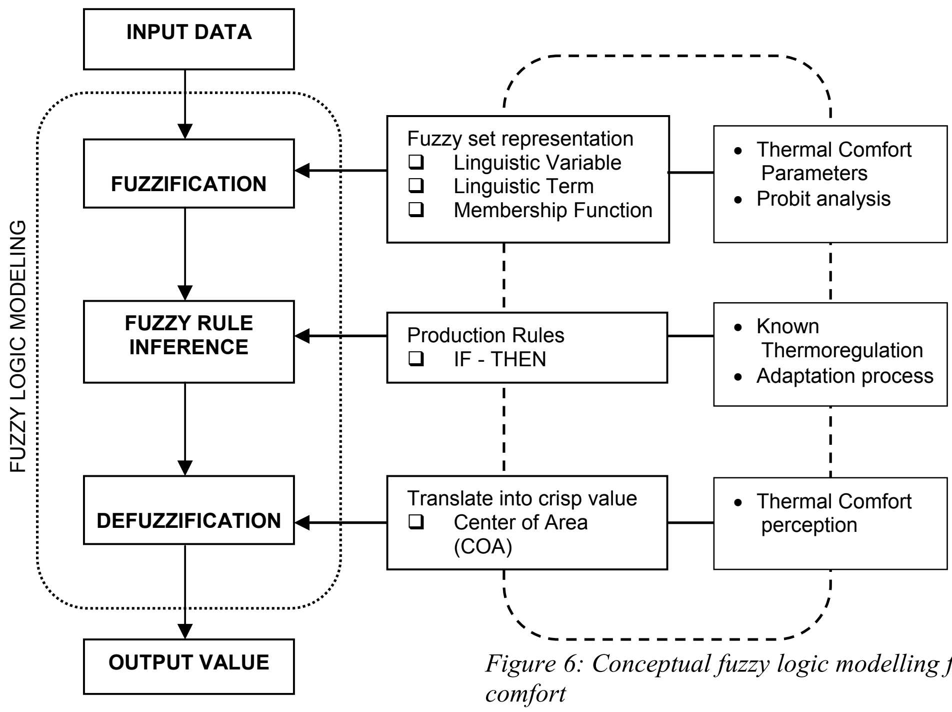

Figure 6: Conceptual fuzzy logic modelling for thermal comfort

Fuzzification

In everyday life, human always deal with linguistic variable to reflect their perception on certain phenomenon. For example, when they need to give an opinion about room air temperature, they may answer as ‘hot’, ’warm’, ’cool’, ’cold’, ‘slightly cool’ etc. A fuzzy set is used to interpret that linguistic value. To make things discrete, it is assumed that each perception is rated by a number in set of X = {0, 0.1, 0.2, 0.,3 ….., 1}. The linguistic value ‘hot’ is then defined to be the fuzzy set of rates living in the universe X.

The degree to which crisp value belongs to a given fuzzy set is represented by function known as a membership function (MF). The MF is a curve that defines how each point in the input space is mapped to a membership value (or degree of membership) between 0 and 1. Many different types of MF curves are available for these applications such as triangular, trapezoidal, Gaussian distribution curve etc.

In this fuzzy logic modelling, it is essential to choose proper MF function in order to develop a good thermal comfort modelling. The previous sections on data analysis had presented the effectiveness of probit analysis to generate useful information about people response to particular environmental stimulus (see Figure 3 to 6). The above statistical results are used as basis in defining MF in fuzzification process.

The transformation process from probit analysis into membership function are based on the following considerations,

- The proportions of probability in probit curve are considered as fuzzy set inputs which inform about the partial membership in them.
- The highest values of probability in probit curves correspond to the maximum degree of membership values in fuzzy sets. It is believed that the maximum value of likelihood of perception votes (outcomes) basically indicates the highest degree of memberships (1).
- The probit curve shapes are best represented by Gaussian distribution functions (curves) in the programming of MF using Mathlab® software.

Shape of the membership function used is Gaussian distribution curves in order to reproduce the shape of probit curves. The X-axis input variable for DBT and MRT is $20^0 – 40^0$ C in order to include wider range of possible temperature in the tropics. Figure 7-10 depicts membership function plots for DBT, MRT, RH and Wind speed.

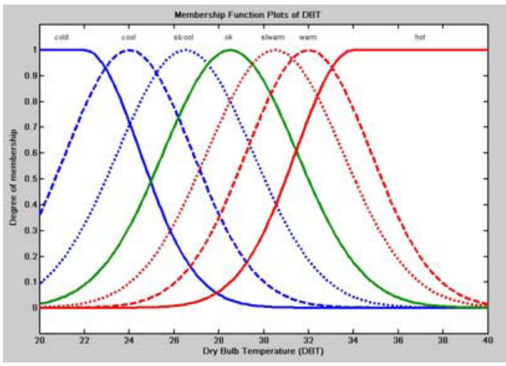

Figure 7: Membership function plots of DBT

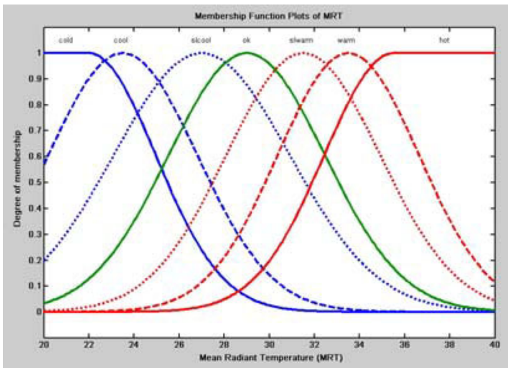

Figure 8: Membership function plots of MRT

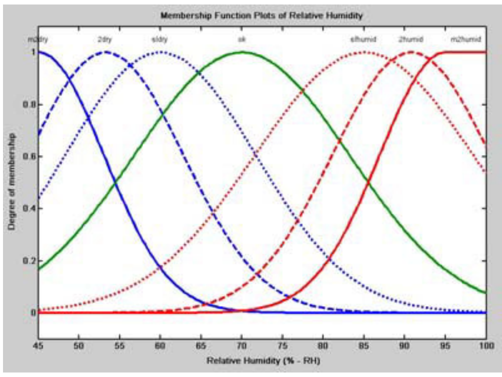

Figure 9: Membership function plots of RH

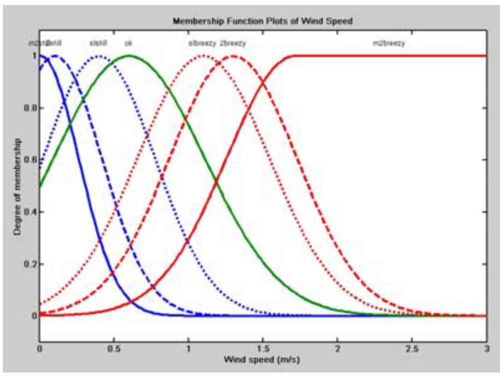

Figure 10: Membership function plots of wind speed

Fuzzy Inference

Zadeh introduced the theory of approximation reasoning. This theory provides a powerful framework for reasoning in the face of imprecise and uncertain information [Zadeh 1975]. Central to this theory is the concept of the fuzzy IF-THEN rule, which is a mathematical interpretation of the linguistic IF-THEN rule. A linguistic IF-THEN rule is a linguistic sentence that is written in simple form such as:

If “X” is A and “Y” is B, then “Z” is C

Here X, Y, Z are input variables, and A, B and C are the corresponding linguistic values. The rules identify the names of the variables X,Y and Z with the universes in which the fuzzy values A,B and C live.

Fuzzy production rules are used to represent the relationships among the linguistic variables and to derive actions from sensor inputs. Production rules consist of precondition (IF-part) and a consequence (THEN-part). The IF-part consist of more than one precondition linked together by linguistic conjunctions like AND and OR. Using the conjunction AND for MINimum and OR for MAXimum is often appropriate in modelling application [Nguyen et.al 1999].

Interpreting if-then rules is a three-part process which can be explained as follow:

1. *Fuzzify inputs*: Resolve all fuzzy statements in the antecedent to a degree of membership between 0 and 1.
2. *Apply fuzzy operator to multiple part antecedents*: In this model, there are multiple parts of the antecedent, therefore fuzzy logic operators are applied to resolve all the antecedents to a single number between 0 and 1. This is the degree of support for the rule.
3. *Make use of implication method*: the degrees of support for the entire rules were applied to shape the output fuzzy set. The consequent of a fuzzy rule determines an entire fuzzy set to the output. This fuzzy set is represented by a MF that is chosen to indicate the qualities of the consequent. If the antecedent is only partially true, (i.e., is assigned a value less than 1), then the output fuzzy set is truncated according to the minimum implication method.

The numbers of rules in the fuzzy production rules depend on the total number of linguistic variables (each input variable has 7 linguistic variables). Total numbers of possible rules based on input variables and linguistic variables is about 720 combinations of rules. It is impractical and unnecessary to include all the possible rules in the modeling. This model has used 14 rules which are believed to be sufficient to reflect on the human thermoregulation of people living in the tropical naturally ventilated buildings (see Table 2).

The following graphs show the dynamic combination of two inputs in affecting thermal comfort perception. Figure 11 presents a three-dimensional curve which represents the mapping from MRT and DBT as inputs (axis X and Y) and ‘Feel’ as an output (axis Z).

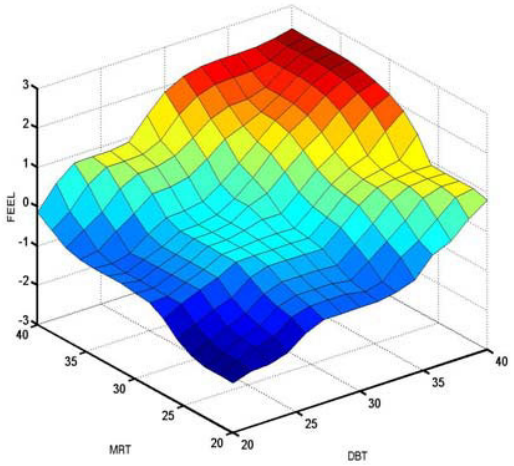

Figure 11: Three dimension curve of MRT and DBT

Figure 12 displays the dynamic correlation of wind speed and DBT on thermal comfort perception. It is shown that higher wind speed (>1.5 m/s) can help to reduce the uncomfortable warmer thermal environment.

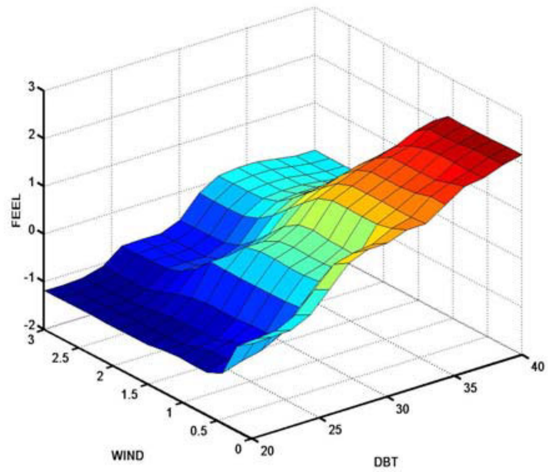

Figure 12: Three dimension curve of Wind speed and DBT

Defuzzification

The result produced from the evaluation of fuzzy rules is, of course, fuzzy. Membership functions are used to retranslate the fuzzy output into a crisp value. This translation is known as defuzzification and can be performed using several methods. The method adopted in this model is Centre of Area (COA) Defuzzification Technique. This method is also known as centre of gravity or centroid defuzzification. This is the most widely used technique and is proven to be reliable in this study. The COA defuzzification technique can be expressed as:

$$x^* = \frac{\int \mu_i(x)x \quad dx}{\int \mu_i(x)dx}$$

Where x* is the defuzzified output, μ_i (x) is the aggregated membership function and x is the output variable. The diagram of the whole computational fuzzy modelling is presented in Figure 14. The COA defuzzification is applied to the output area (black curve in right bottom of the diagram).

VALIDATION

Finally, to demonstrate the model's robustness, it is essential to validate the output by using different set of survey data (200 samples). Similar to PMV prediction, the model uses the six parameters of thermal comfort as inputs and computes the prediction votes. The outputs were compared to the actual survey votes (ASHRAE scale). The result is presented in Figure 13.

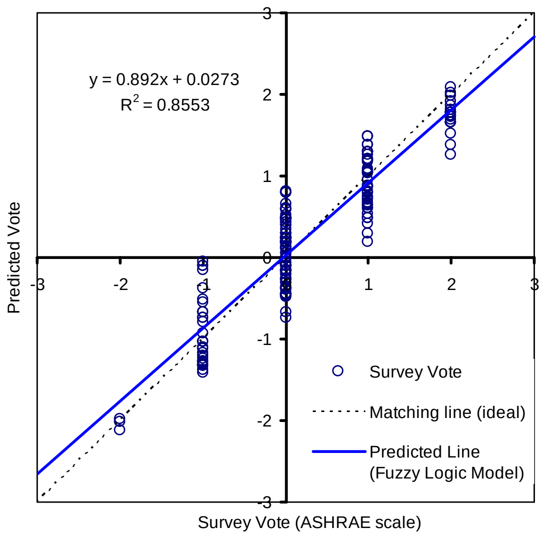

Figure 13: Model validation

Prediction votes based on fuzzy logic modelling has demonstrated a very good correlation with the actual survey votes (R^2=0.8553). Therefore the model can be used in future to predict thermal comfort in tropical NV buildings. Nevertheless, some discrepancies are inevitable due to some reasons:

- The facts that survey votes are based on subjective human perception which might vary between persons.
- The actual survey vote is discrete number (based on 7 scales) meanwhile the predicted output is not discrete (continuous) number.

CONCLUSIONS

Fuzzy Logic has been used to model human imprecise linguistic variable in thermal comfort perception. The Probit analysis is used to examine the probability of human response under different environmental conditions and to provide fundamental information for developing MF in fuzzification process.

The proposed model is found to be suitable for evaluating thermal comfort perception of the occupants in residential NV buildings in the tropics. Further application for different functionality such office, schools etc requires further validations. Certainly, this will be the focus of model development in the near future.

REFERENCES

CEN-ISO 7730.1995. Moderate Thermal Environments – Determination of the PMV and PPD Indices and Specification of the Conditions for Thermal Comfort.

Feriadi H, Wong, N.H, Chandra, S, Cheong, K.W, 2003. Adaptive Behaviour and Thermal Comfort in Singapore's Naturally Ventilated Housing. Building Research&Information Journal v: 31, 13-23. Spon Press

Finney, D.J. 1962. Probit Analysis. Cambridge University Press. UK.

Kosko B. 1993. Fuzzy Thinking – New Science of Fuzzy Logic, Hyperion Publishers, New York.

Nguyen, H.T, Elbert A. 1999. A First Course in Fuzzy Logic. Chapman &Hall/CRC.

Zadeh, L.A., 1965. Fuzzy Sets. Information and Control. Vol 8(3). 338-353.

Zadeh, L. A., 1975. Concept of Linguistic and Its Application to Approximate Reasoning, Information and Science vol 8-9.

Table 2: Fuzzy If-Then Rules

Rules		DBT	MRT	RH	Wind	Met	Clothing		Feel (sensation)
		Antecedents (Precondition)							**Consequents**
1	***if***	Cold	Cold	Much too dry	Slightly still	Low	Thin	***then***	Cold
2	***if***	Cold	Cold	Too dry	Slightly breezy	Slightly Low	Slightly thin	***then***	Cold
3	***if***	Cool	Cool	Slightly dry	Too breezy	Slightly high	Slightly thin	***then***	Cool
4	***if***	Cool	Cool	Just right	Slightly breezy	Slightly low	Thin	***then***	Cool
5	***if***	Slightly Cool	Slightly Cool	Slightly dry	Just right	Medium	Slightly thin	***then***	Slightly cool
6	***if***	Slightly Cool	Slightly Cool	Just right	Slightly breezy	Medium	Average	***then***	Slightly cool
7	***if***	Neutral	Neutral	Just right	Slightly breezy	Slightly high	Slightly thin	***then***	Neutral
8	***if***	Neutral	Neutral	Just right	Just right	Medium	Average	***then***	Neutral
9	***if***	Slightly Warm	Slightly Warm	Too humid	Too breezy	Slightly high	Average	***then***	Slightly warm
10	***if***	Slightly Warm	Slightly Warm	Slightly humid	Slightly still	Medium	Slightly thin	***then***	Slightly warm
11	***if***	Warm	Warm	Too humid	Slightly still	Slightly high	Slightly thick	***then***	Warm
12	***if***	Warm	Warm	Much too humid	Too still	Medium	Average	***then***	Warm
13	***if***	Hot	Hot	Much too humid	Too breezy	Slightly low	Thin	***then***	Warm
14	***if***	Hot	Hot	Much too humid	Too still	High	Thick	***then***	Hot

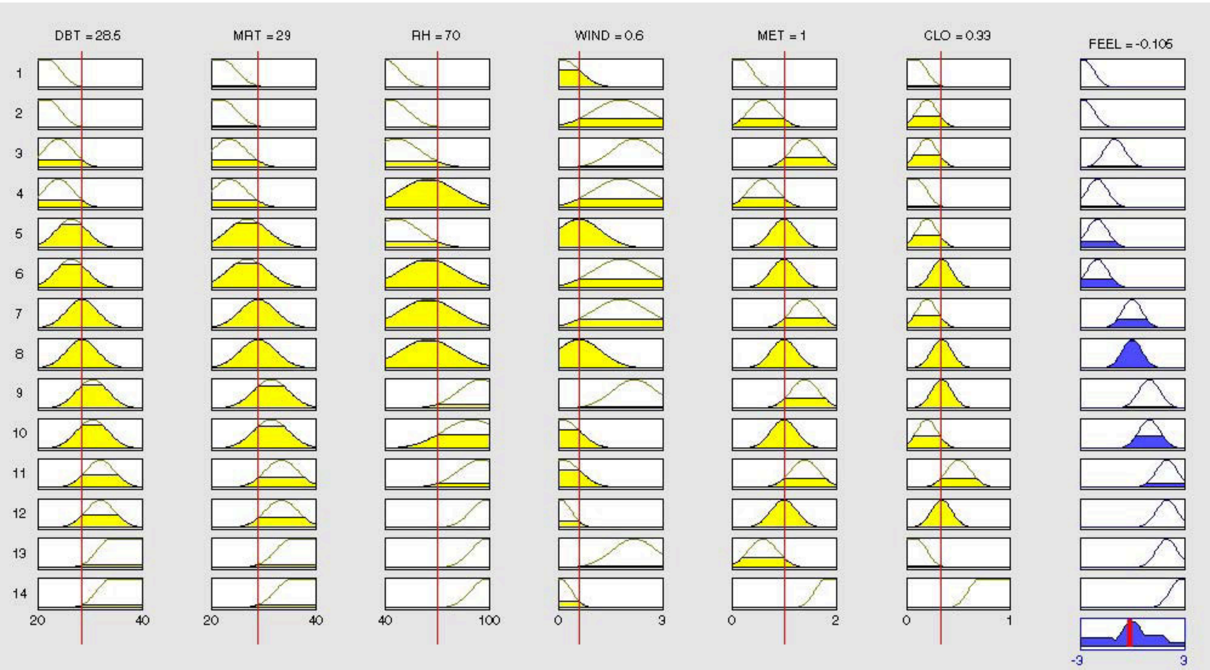

Figure 14: Fuzzy rule views