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Fuzzy modeling and control of HVAC systems – A review

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Paper presents role of fuzzy modeling in heating, ventilating and air conditioning (HVAC) and control models. HVAC design professionals are required to evaluate numerous design alternatives and properly justify their final conceptual selection through modeling. This trend, coupled with the knowledge of experienced designers, increasing complexity of the systems, unwillingness to commit additional funds to the design phase itself, can only be satisfied by approaching the conceptual design process in more scientific, comprehensive and rational manner as against the current empirical and often adhoc approach. Fuzzy logic offers a promising solution to this conceptual design through fuzzy modeling. Numerous fuzzy logic studies are available in the non- mechanical engineering field and allied areas such as diagnostics, energy consumption analysis, maintenance, operation and its control. Relatively little exists in using fuzzy logic based systems for mechanical engineering and very little for HVAC conceptual design and control. This review appraises recent advances on the specific areas of conceptual design and control involving synthesis of HVAC components.

Keywords: Fuzzy algorithm, Fuzzy logic, Fuzzy modeling, HVAC, Intelligent control

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Introduction

Fuzzy logic has its roots in the multivalued logic systems developed by Lukasiewicz in 1930's. The foundation of fuzzy logic techniques for engineering applications has been laid down in 1965 through the concept of fuzzy sets[1] and in 1968 through fuzzy algorithm[2]. A conceptual framework for dealing with systems, which are too complex or too ill defined to admit of precise quantitative analysis, has been developed[3-5]. There were many basic aspects like role of fuzzy feedback, execution of fuzzy algorithms, execution of fuzzy algorithms by humans, conjunction of fuzzy instructions, assessment of the goodness of the fuzzy algorithms, the implications of the compositional rule of inference and the interplay between fuzziness and probability in the behavior of humanistic systems[6-9].

Fuzzy systems are capable of approximating any real function on a compact fuzzy subset. Such approximators have often been found superior to conventional modeling, especially when information being processed is inexact and uncertain[10-13]. Main advantages of fuzzy logic in approximator, as compared to conventional approaches, is that no mathematical model is needed, and it is possible to use all available information about the process in the design of the fuzzy approximator scheme. A fuzzy logic approximator converts a set of linguistic rules, based on expert knowledge, into an automatic approximation strategy. Employing fuzzy IF-THEN rules can model qualitative aspects of human knowledge and reasoning processes without employing precise quantitative analysis[14-16]. Status of fuzzy logic in 1998 is vastly different than that in 1978. Mathematical tools of fuzzy logic are established[17] and basic theory is in place. Fuzzy logic based applications are ranging from consumer products and industrial systems to biomedicine, decision analysis and recognition technology[18].

Knowledge Base and Fuzzy Logic

Knowledge base (KB) is structured in the frames or schema, which represent the operator knowledge about the plant in the form of geometrical structure (connections, locations, states of components), process representations (variables behaviors, casual relations, functional landmarks and threshold), and control sequences (actions, tasks, procedures and

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respective effects). Two types of frames distinguished are: i) Knowledge frames that describe processes and structure of the system only in terms of general physical and engineering principles, as well as rules of thumb; and ii) Rule-frames that account for all the operator's interaction with the system, in that they encompass pre-definite plans of actions for different situations. A large range of rule-frames is assumed to be present in the KB of the operator[19].

It is feasible and beneficial to develop a KB program for the automatic analysis and correction of HVAC system simulated performance without going in for its mathematical modeling. This was confirmed with the case study of cooling coil, which was restricted to operation and performance analysis at the peak load operation of coil. Rules implemented for assessing the performance proved to be reliable. Coupling between components, design conditions and design parameters are the major obstacles for the KB analysis and rules implementation in correcting the system performance[20].

Fuzzy Logic and Nonlinear System

Fuzzy controllers can control nonlinear process model and time-delay process model significantly better than linear controller[21]. Eliminating most of the trial-and-error efforts, previously associated with construction of fuzzy control system, a practical design procedure has been developed to systematically design nonlinear fuzzy controller with either linear or nonlinear control rules for processes whose mathematical models are unknown[22]. Fuzzy modeling methods for nonlinear system identification and control design from process data were reviewed and attention was paid to the choice of a suitable fuzzy model structure for the identification task[23]. A general class of nonlinear fuzzy logic controller (FLC) was designed by specifying some design choices for fuzzy system[24]. An algorithm has also been proposed for FLC design. A control policy for nonlinear systems was generated by developing a number of local linear models and designing optimal control policies for each of these local models[25].

Development Trends of Fuzzy Rule-based Models

Fuzzy rule base (FRB) is the heart of fuzzy control system since all design parameters are used to assist and interpret these fuzzy rules and make them usable to design a fuzzy controller for a specific control problem. First major attempt was to generate fuzzy rules from numerical data and to combine numerical and linguistic information into a fuzzy rule base[10]. Fuzzy rules for a class of complex and ill-defined systems where mathematical models are unknown can also be generated from the rule-generated function and the input/output scaling factors as obtained from a genetic algorithm[11]. The study of accuracy and complexity of the fuzzy system derived by the self-organized fuzzy rule generation procedure (SOFRG) has shown better results comparatively[12]. Another approach of the automatic generation of FRB models has been developed and validated on a real cooling coil subsystem.

The accuracy of the model on validation data is reasonable[13]. In practical applications, more attention has been paid as how to construct a suitable rule base for a given task. Several approaches have been proposed to identify FRB's automatically[15-17,26]. An approach of evolutionary design of FRB has simplified and introduced more accuracy in the identification of optimal FRB[14]. Existing expert knowledge could easily be incorporated into the model. A new encoding mechanism is used that allows the fuzzy model rule base structure and parameters to be estimated from training data without establishing the complete rule list. It uses rule indices and therefore significantly reduces the computational load. It makes the resulting model as flexible. The existing expert knowledge could easily be incorporated into the model at initialization stages and makes FRB model as flexible as other black box models[27,28].

Advancements in Fuzzy Modeling Approach

Qualitative modeling has been one of the most important issues since the beginning of fuzzy theory. Zadeh[1] in 1965 suggested an idea of fuzzy algorithms, which are qualitative descriptions of a human actions or decision-making. Motivated by the ideas of fuzzy algorithms and linguistic analysis, Mamdani[29] first applied fuzzy logic to control, which was taken as fuzzy modeling or qualitative modeling. For fuzzy model identification existing methods of statistical approach and neural network based approach were used and next to it was intended to use genetic algorithms for identifying the structure of fuzzy model and its parameters[17,30].

Fuzzy technique leads to promising results, which were motivation toward the development of fuzzy modeling and control in coming years[31]. Altrock[32] in 1996 proposed that development of fuzzy-logic systems involves specific design steps as follows: i) *Design inference structure*— Specify how the output variables connect to input variables by the rule blocks; ii) *Define linguistic variables*—Variables form the vocabulary used by the fuzzy-logic rules expressing the control strategy; iii) Create an initial fuzzy-logic rule base using all available knowledge on how the system should perform; iv) *Debug, test, and verify the system offline for completeness and nonambiguity* —Use a software simulation or sample data of the process if it exists in this step; and v) *Debug online*—Connect the fuzzy logic system to the process under control and analyze its performance in operation.

Cao *et al*[33] proposed a new method to design a fuzzy controller based on the dynamic fuzzy-state space model. Fuzzy clustering method is used for structure identification of fuzzy model[15]. Linguistic approximation method was further taken up for improvements. A common approach was used to extract structural and parametric information. In these techniques, rules had been identified with a cluster in the I/O product space. These identified rules act as the link between parametric and structural representation of inference information[34]. Moser & Navara[35] observed that by employing a fuzzy conjunction instead of a fuzzy implication, Mamdani 's approach[29] does not represent the logical meaning of a linguistic IF-THEN rule. Standard inference mechanism due to Mamdani seems not to be always a satisfactory fuzzy interpolation under practical conditions. So they modified the Mamdani inference by changing the scales of membership functions and by replacing the degree of overlapping with the truth-value of a corresponding (many-valued) conditional statement.

Cao *et al*[36] carried identification of the membership functions including the estimation of number of rules and parametric estimation in membership functions and determination of structure and parameters of the rule maps of local linear models. Takagi & Sugeno[17] model in 1985 was based on "fuzzy partition" of input space. But Sugeno & Yasukawa's model[15] actually has singletons as consequent parts; it needs more fuzzy rules and has poorer capability of system description than Takagi & Sugeno's model[17]. Kim *et al*[37] developed a new fuzzy modeling algorithm, which has an excellent capacity to describe a given system, uses a few fuzzy rules, and is easy to implement in a digital computer.

A new approach of modeling formalism was introduced to highlight the similarities between fuzzy systems and hybrid control systems and also link fuzzy control to the well-established field of dynamical systems and the rapidly evolving field of hybrid control[38]. In 1998, fuzzy rules were generated through Fuzzy C-means (FCM) clustering algorithm[39], and a clustering technique (Fuzzy Line Clustering) was introduced to assign the input membership functions. For MBPC (model based predictive control) application to nonlinear systems, fuzzy MBPC[40] were proposed with Takagi-Sugeno fuzzy models. Wong & Fan[41] considered an effective method, based on GA (Genetic algorithms), where rule mapping fuzzy control structure is proposed to simultaneously select an appropriate rule base and membership functions of the considered fuzzy system in order to have good overall performance. Within the domain of evolutionary algorithms (genetic algorithms, genetic programming, evolution strategies, evolutionary programming) coevolutionary algorithms have received increased attention. But still further to combine the search power of coevolutionary computation with the expressive power of fuzzy systems, a novel algorithm, Fuzzy Cooperative Coevolution is introduced to hard real problems, which is likely to become a powerful tool in the fuzzy modeler's toolkit[42]. For high nonlinear dynamic system, a new flexible fuzzy algorithm has proved to be useful to identify with high accuracy the high nonlinear dynamic systems[43]. For use of fuzzy decision making (FDM) in model predictive control (MPC), Sousa & Kaymak[44] investigated that this technique is better than conventional MPC. Nonlinear dynamics system of air-conditioning has also shown that the performance of the model predictive control can be improved by the use of fuzzy criteria in a fuzzy decision making framework.

Fuzzy system has also been made to model the higher levels of hierarchical systems as conventional feedback at lower level, supervisory operations at middle level and planning at top level[45]. Development of a hierarchical system has been thought as a refinement of simple linguistic models. The use of the structure of KB of FRB systems in hierarchical systems has made it more flexible. This concept does not change the meaning of the linguistic variables, it just represents the information in a more accurate way. This methodology has improved the modeling of those problem subspaces where the former models have bad performance[46,47]. Sanz[48] developed a reduced model of the thermal dynamic behavior of a building, with a central heating system under several climatic conditions. The model has been validated as a realistic test-bed for analyzing control strategies of hierarchical control structures. In 2003, Huaguang &Yongbing[49] introduced concept of fuzzy hyperbolic model (FHM), which is nonlinear in nature and can be derived using a set of fuzzy rules. FHM combines the merits of fuzzy model, neural network model and linear model. Model accuracy and interpretability was the problem associated with local models liberalizations of nonlinear systems. An attempt[50] has been made for modeling and identification of nonlinear model with multiobjective algorithms. For improving the transparency in the model, evolutionary computing and gradient-based learning of fuzzy neural networks were introduced[51]. Tang & Diaz[52] in an attempt to introduce robust fuzzy control for mechanical systems to track a smooth desired trajectory tried the control by combining advantages of FLS, adaptive controls and robust controls. Kohn-Rich *et al*[53] contributed for the design of robust fuzzy control laws for a large class of mechanical systems and used Lyapunov stability theory to ensure closed loop stability.

Research into Fuzzy Modeling of HVAC Control

For cold store application of HVAC, Becker *et al*[54] designed a fuzzy controller for temperature and relative humidity (RH) in refrigeration system by considering their thermodynamic coupling. An attempt has also been made to replace the linear proportional control by fuzzy control for maintaining interior environment of automobile[55]. Fuzzy controller is designed to control blower speed with dependency on engine coolant temperature and in-car set point. A new approach[56] of fuzzy timing, Petri Net, for distributed temperature control to achieve optimum air temperature inside a car considering the comfort for each passenger, has also been developed. Optimum HVAC control is applied to AC system for a car and fuzzy controller is used to independently control temperature at various locations inside a car. Arima *et al*[57] employed HVAC system controller with a control algorithm using fuzzy logic reasoning and rough set theory. Fuzzy logic reasoning has shown better performance in both temperature and RH control than rough set method.

The fuzzy reasoning expert system[58] has been applied in the building for the achievement of thermal and visual comfort. Attempt[59] has also been made to implement a fuzzy controller for naturally ventilated buildings using MATLAB™. Fuzzy controller is capable of providing thermal comfort inside the room. Lea *et al*[60] contributed to lay down outline of the conceptual design of HVAC control system based on fuzzy principle and attempted to regulate the zonal comfort level based on temperature and RH.

In 1996, Altrock[61,62] worked for the design of fuzzy controller for replacing conventional thermostat by fuzzy logic thermostat. This design, which find applications in automobile engineering, has led to an energy saving (3.5%) and comfort level was enhanced. Mraz[63], in 2001, presented one of the alternatives for a fast transition from classical thermostatic control to digital control of the refrigerating compressor on the basis of a fuzzy controller. Betzaida & Miguel[64] worked on a nonlinear controller for a variable air volume (VAV) flow in HVAC system which is capable of maintaining comfort conditions within a thermal space with time-varying thermal loads acting upon the system. Liu *et al*[65] worked for the improvement of the refrigerant flow control method by using an electronic expansion valve (EEV) and employing the fuzzy self-tuning proportional-integral-derivative (PID) control method. Experimental results show that the new control method can feed adequate refrigerant flow into the evaporator in various operations. The evaporator discharge air temperature has dropped by approx 3°C as compared with that of the conventional PID control system. Wu *et al*[66] also worked on the control of EEV with fuzzy techniques using dynamic model of multi-evaporator air conditioners. Sousa *et al*[67] worked on fuzzy predictive control scheme based on a fuzzy model of a process and a discrete optimization technique (branch-and-bound), combined with an inverse model control law and applied this technique to an HVAC system consisting of a fan-coil unit installed in a test cell. A sugeno-fuzzy controller[68] based on identified fuzzy model, resulted in better and constant performance overall the operating range of fan-coil unit. On its domain of validity, fuzzy controller behaves better than classical controller. In general, sense HVAC control strategy has been taken as to control air temperature and RH[55-62]. Hamdi *et al*[69,72] have developed the concept of controlling indoor thermal comfort based on the human sensation. The fuzzy comfort model is deduced on the basis of learning Fanger's 'Predicted Mean Vote' PMV equation.

A new simple approach for HVAC system[73], focused on the application of an adaptive fuzzy controller and aimed at the control of the indoor thermal-hygrometry comfort conditions, shows a very stable behavior, allowing an effective and fast control of the indoor microclimate conditions. Fuzzy logic control has also been applied in road tunnel environment[70] to control ventilation. Yang & Huang[71] raised the concept of dual fuzzy controller, first to control the stroke and other to control phase of a linear compressor. Thermal performance of refrigeration compressors has also been predicted by fuzzy techniques. The simple fuzzy model and the compound fuzzy model, which comprises the theoretical model, can produce better effect than the classical thermodynamic method[74]. Aprea *et al*[75] studied fuzzy compressor of vapor compression refrigeration plant in the environment of cold store, and observed that significant energy saving on an average has been obtained using the compressor speed control algorithm based on the fuzzy logic. Wu *et al*[66], studied that grip of the fuzzy control on the compressor is far better. A self-tuning fuzzy control algorithm with a modifying factor was incorporated in the controller for compressor speed and electronic expansion valves regulation. A controllability test showed that the control strategy and algorithm are feasible and can achieve desirable control results[66].

A fuzzy control strategy for an HVAC adjustable speed drive system, while maintaining suitable thermally comfortable conditions, could reduce energy consumption. Simulation has proved that using a variable air volume greatly decreases amount of energy while considering the subjectivity of human sensation[76]. An optimal combination of the characteristics of an AC system and the control strategy is necessary to minimize costs and the energy demand. Therefore, a sequential control for such a system was developed, tested by simulation runs with TRNSYS, and implemented in an existing plant. For comparison, TRNSYS had to be combined with MATLAB, which includes some optimization tools[77]. Gates *et al*[78] identified design parameters for fuzzy-based control of staged ventilation systems. A simple non-steady state heat balance is used in conjunction with a broiler house simulation model, and coupled with a model for the control system, to simulate control system performance. Comparisons between the new fuzzy stage controller and conventional staged control indicate the betterness of fuzzy control.

Fuzzy control is becoming an efficient way to implement the control process in HVAC. The functioning fuzzy subset inference (FFSI) based fuzzy control was verified as effective method to be used in HVAC[79,80]. Fuzzy controller was found to be capable for fine control[81] to provide thermal comfort and adequate air distribution inside a single-sided naturally ventilated test room. Fuzzy control applied in potato stores to keep the storage climate in appropriate condition and for energy saving was found advantageous to adapting fuzzy control[82]. On comparing the performance of 5 fuzzy controllers (P, PID, PI, PD, adaptive PD), Fuzzy P ensures the lower energy consumption and has satisfied the indoor comfort requirements[83]. To cope with nonlinearity and time varying characteristic of HVAC process, multiple model approaches have been found more appropriate[84-86]. He *et al*[87]proposed a multiple model predictive control (MMPC) for AHU (Air Handling Unit) temperature control, which could meet the control performance requirements at different operating points.

Conclusions

Fuzzy techniques have gained increased attention in HVAC, automobile, building, cold stores, AC and in tunnel ventilation etc. Attention is still required towards hybrid control, vapour compression refrigeration as integrated system, closet environment of HVAC in order to improve control strategies using fuzzy techniques. Fuzzy logic control requires further investigation as to their application to the HVAC system. The energy efficiency for different applications is also to be investigated.

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