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An Experimental Liquid Cooling System Dynamic Simulator for the Evaluation of Intelligent Control Techniques

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Refrigeration systems are required in most chemical industries in order to maintain the temperature in process equipments, production line, air-conditioned environments or rooms, etc. The main drawback of the refrigeration systems is the great energy requirement. Aiming at minimizing these costs, several works have been reported in the literature using variable speed compressors. This study applied the commercial software ASPEN PLUS® and ASPEN PLUS DYNAMICS® to simulate an experimental chiller prototype. The first software was used to simulate the steady state condition, while the latter one was used to evaluate the open loop and closed loop dynamics of the cooling process. The geometries of heat exchangers were obtained from the software EXCHANGER DESIGN AND RATING®, also included in the package ASPEN®. Once validated with experimental data, the simulator was used to the performance assessment of the classical control strategies application using variable speed compressor. It was also proposed the use of fuzzy logic-based control. It was used a two-term fuzzy control, that is suitable for nonlinear processes and is based on the plant expert knowledge. The fuzzy controller proved to be effective in controlling the system under different operating conditions.

1. Introduction

Refrigeration systems are required in most chemical plants. They are used to maintain equipments, products or even certain environments in a temperature set point. The main drawback of the refrigeration systems is the great expense of energy. In some industries, spending on energy can represent up to 70% of total energy consumption. According Schurt (2010), 10% of all energy produced in the world is consumed by cooling processes. This high energy consumption has motivated developments on more efficient control techniques which are able of improving such systems operation.

The great issue on the chiller control system design is related to its nonlinear features, which makes the on-off and the conventional PID controllers unsuitable. To overcome this problem, intelligent control systems, which are able to adapt themselves to different operating conditions, could be successfully applied to follow the set point value, even though the process behaviour is unfamiliar or unexpected. Fuzzy logic and artificial neural networks are usual mathematical approaches applied in the development of intelligent controllers. These techniques try to incorporate the human expertise in the control system design. A typical fuzzy controller can be designed to behave as deductive or inductive reasoning. In the first process, human beings use their knowledge to conclude something, whereby in the inductive reasoning it is possible to infer conclusions from learning and generalization of particular observations, such as the transient process behaviour (Shaw and Simões, 1999). According to Cosenza and Galluzo (2011), despite of traditional approaches present many difficulties connected with the restrictive applicability conditions and the computational complexity, nonlinear control techniques have received considerable attention in the industrial process field in the last decade.

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On the other hand, the use of variable speed compressors, through frequency converter devices, turns the refrigeration systems control more efficient, as shown by Manske (2001). The author compared the on-off compressor operation to a variable rotation control in order to keep the condensing temperature. It was proved in this study that the use of the frequency converter reduced the energy demand by 8%.

There are two types of two-term fuzzy control: fuzzy-PD and fuzzy-PI. The first one calculates control output (U) from error (E) and error variation, being considered a positional control. In the second one, an incremental output is computed, so that is considered a velocity control (Figure 1a). The fuzzy-PI is recognized as the most practical fuzzy control due to the ability to remove the response offset, despite a poor performance in the transient response in higher-order processes due to the internal integration operator (Li and Gatland, 1996). In the present work, the fuzzy-PID was implemented by coupling fuzzy-PI to fuzzy-PD, as shown in Figure 1b.

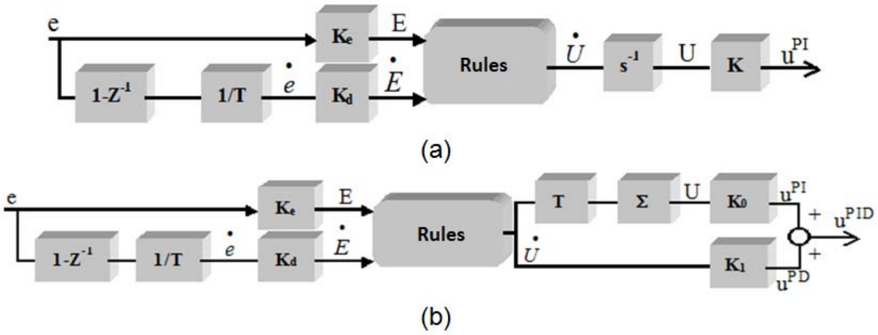

Figure 1. Digital structure of (a) fuzzy-PI controller and (b) fuzzy-PID controller.

In order to study cooling processes, an experimental prototype of a chiller, (Pinelli, 2008) was set and automated to extract data and develop researches. In the present study, a model was developed in ASPEN ® software which is able to simulate the previously mentioned prototype. Once validated, the dynamic model was exported to MATLAB ®, so that, using the SIMULINK toolbox, forms of classical and intelligent control were implemented to control the temperature and the system behaviour could be evaluated.

2. Experimental prototype

In this study, a computational simulation of an experimental refrigeration plant prototype located at the Process Control and Automation Laboratory at School of Chemical Engineering (UNICAMP) was developed. In this plant, showed on Figure 2(a), the primary cycle is based on a refrigerant fluid (R22), which circulates through the cycle components (compressor, condenser, expansion valve and evaporator), removing heat from the fluid to be refrigerated (secondary fluid) and providing heat through the water condenser. The secondary fluid line consists of a storage tank and a pump that drives the fluid (an aqueous solution of propyleneglycol 50% v/v) through the evaporator.

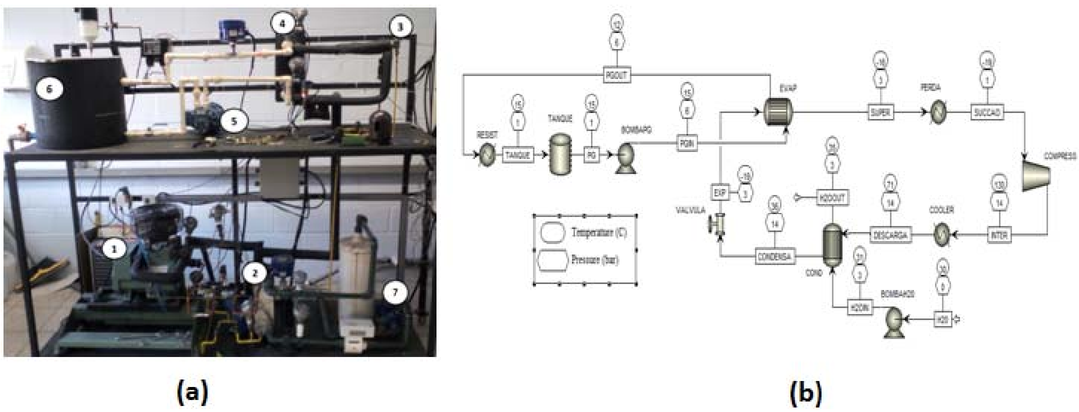

Figure 2. (a) Experimental prototype of the liquid cooling system: 1-compressor, 2-condenser, 3-expansion valve, 4-evaporator, 5- pump of secondary fluid line, 6-propylene glycol solution storage tank, 7-pump of condensation line; and (b) flowsheet developed in Aspen Plus ® for the cooling system modelling

3. Computer Modelling

The EXCHANGER DESIGN AND RATING® (EDR) software (from ASPEN ®package) was used for the geometry design of the heat exchangers. The measured data at the inlet and outlet of the condenser are shown in Table 1. The operating data was crucial to design an exchanger equal to the experimental one.
Exporting the exchanger geometry from EDR, the steady state model for the refrigeration system was developed in ASPEN PLUS® software. The input data provided to this system modeling are shown in Table 2. The flowsheet is shown in Figure 2(b).

Table 1: Operating data used to design the heat exchanger

Variables	Hot fluid		Cold fluid	
	Input	Output	Input	Output
	R22		Solution 50% propylene glycol	
Mass flow (kg/m³)	120		800	
Temperature (°C)	70.0	39.2	31.3	32.3
Pressure (bar)	13.8	12.4	6.0	5.4

Table 2: Refrigeration system input data

Block/Stream	Input Data
SUCCION	Temperature: 1.4°C; Pressure: 1.43bar; Mass flow rate R22: 73kg/h
PGOUT	Temperature: 6.8°C; vapor fraction:0; Mass flow rate: PG: 640 kg/h, H2O: 140 kg/h
COMPRESS	Type: isentropic; performance curves; Initial rotating frequency: 60 Hz
COOLER	Pressure drop: -0.0001bar; Heat Rate: -1086.58W
COND	Calculation method: Trays; hot stream sub cold degrees: 3.0°C
VALVE	output pressure: 2.9bar
EVAP	Calculation mode: Trays; cold stream superheat degrees: 6.0°C
LOSS	Pressure: 1.4bar; Heat Rate: 136.99W
PUMPH2O	Power: 0.5Hp
PUMPPG	Power: 0.75Hp
TANK	Pressure: 1.0bar; Valid phases: only liquid; Initial temperature: 10.0°C
RESIST	Pressure: 1.1bar; Heat rate: 2000W; Valid phases: only liquid

The stationary model was exported to ASPEN PLUS DYNAMICS® software which was able to simulate the transient behavior of the plant. Before being exported to the toolbox of MATLAB®, the model was validated and linearity analysis was carried out.

4. Results

4.1 Validation

Experiments were performed under different steady state conditions in order to prove the accuracy of the model. In each experiment, a disturbance in the thermal load or compressor speed was performed to reach another steady state condition.
The observed variables were inlet and outlet propylene glycol temperature at the evaporator and the evaporation temperature of R22. The variables values were normalized and plotted on a graph comparing the simulated and experimental data, as shown in Figure 3.
The average error is given by the linear coefficient of the straight line, since slope was close to 1. The error obtained was about 2%, which could be considered low for the refrigeration system simulation purposes.

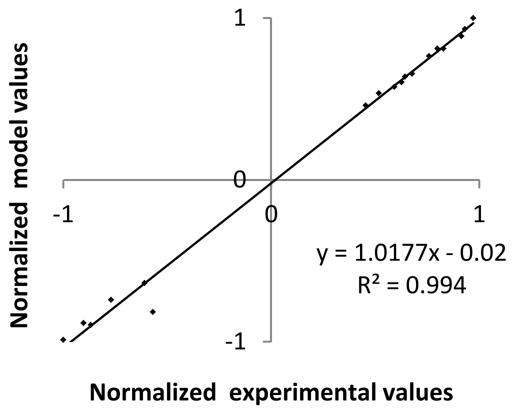

Figure 3. Comparison between experimental and simulation data. Temperature values were normalized from -1 to +1

4.2 Linearity analysis

To observe the open loop dynamic behaviour of the plant, disturbances were applied to the manipulated variable in order to analyze linearity of the system. Because the compressor allows variable speed operation, the manipulate variable was the compressor rotating frequency. The observed variable was the temperature of propylene glycol solution at the outlet of the evaporator, the stream of liquid to be used as coolant utility ("PGOUT" line at Figure 2b).
Figure 4 shows the gains found in the system under disturbances of ± 10%, ± 15% and ± 20% in the rotation of the compressor. For these variables, the slope shows the system has a slightly nonlinear behavior. This means that a well-tuned conventional control may be used, providing the operating condition does not change significantly from its original steady state.
The choice of appropriate method of control demands conducting linearity of the system. A linear behaviour of a manipulated variable indicates that a classical control technique would be adequate to control the process using that variable; otherwise, the control technique being chosen must take into account the nonlinearity of the system.

4.3 Control strategies

Simulations were performed using the developed ASPEN PLUS DYNAMICS simulation as a block in the SIMULINK-MATLAB environment to evaluate and compare fuzzy-PID and conventional PID control technique. The compressor rotating frequency was manipulated to control the temperature of propylene glycol at the evaporator outlet. In order to get closer to reality, a noise signal was applied to this temperature "measurements". Sampling time was set to 6 minutes.

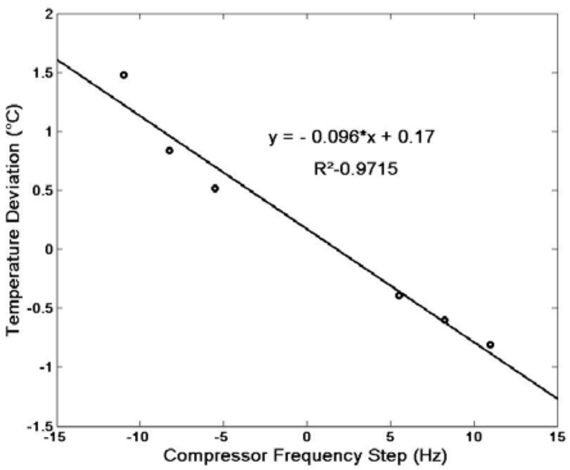

Figure 4. Variable-gain system was obtained between observed and disturbed variable

The tuning of the conventional PID was performed by the Ziegler-Nichols method and the tune parameters were: Kc= 5.09 Hz/^{o}C, τ_i= 0.25 and τ_d= 0.0625. The fuzzy-PID was set based on Mamdani rules, as proposed in LI and GATLAND (1996). It was used seven symmetric triangular shape membership functions. The gains (Figure 1b) were obtained by trial-and-error procedure for the fuzzy-PID system: Ke= 1.5, Kd= 1.7, K0= 0.71 and K1= 0.36. Figure 5 shows the temperature variations under servo control (set-point disturbances around initial steady state conditions).

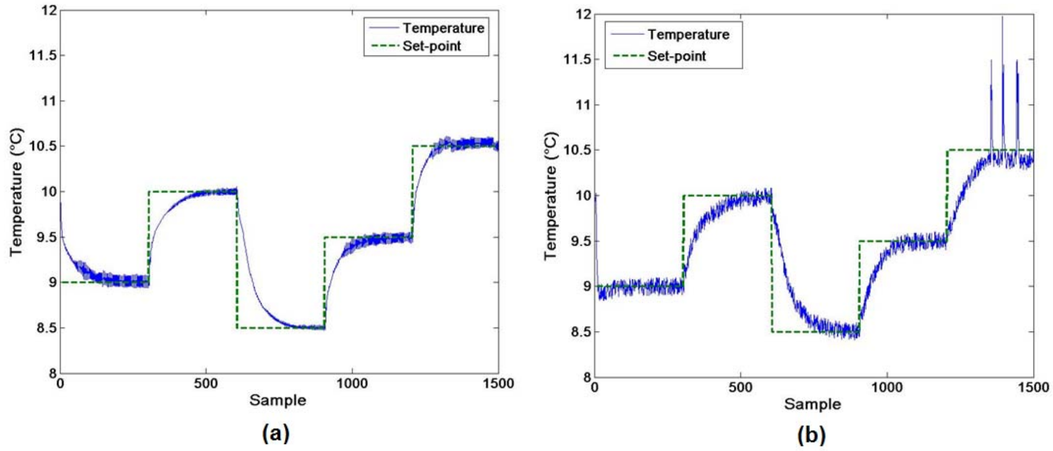

Figure 5. Controlled variable under set-point disturbances, using (a) fuzzy-PID and (b) conventional PID control.

Both controllers were capable of tracking the set-point of the propylene temperature. The only exception was when the set-point was 10.5°C and the conventional PID presented a small off-set. Figure 6 shows the results of regulatory control, when heat load was disturbed.

The fuzzy control showed a slightly faster response compared to classical PID, however both controllers were adequate to reject the imposed disturbances.

Looking for a broader assessment of control performance, a different operating condition was simulated for the chiller. The controllers, originally tuned for conditions of Tables 1 and 2, were implemented and their parameters unchanged. Figure 7 shows the results when set-point was set to 8°C. Once again, the heat load was disturbed. It was observed that the PID control was not able to maintain the temperature on the set-point (Figure 7b). On the other hand, a high performance was obtained by using the fuzzy control strategy (Figure 7a). As expected from the linearity analysis, for this new operating point, the PID must be tuned again.

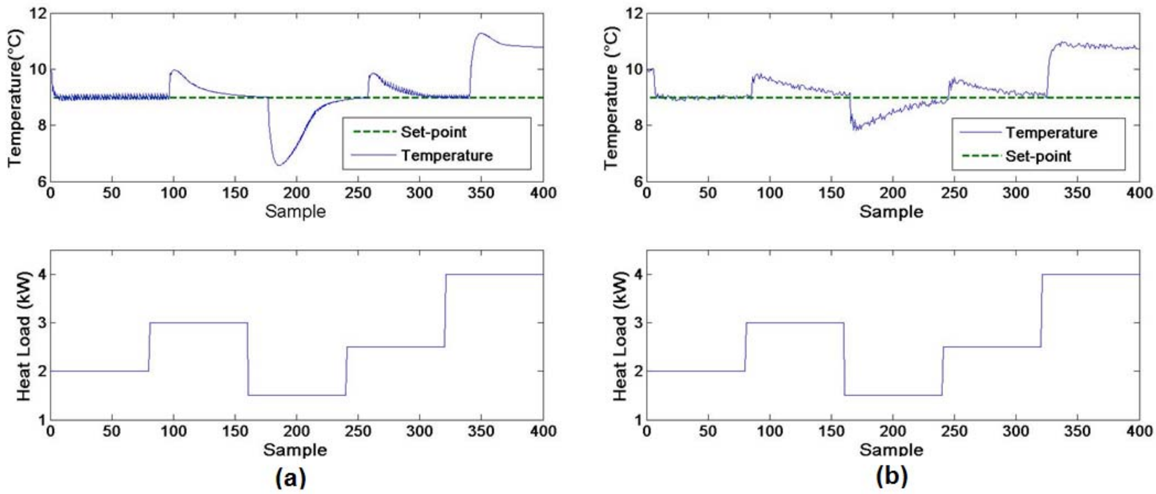

Figure 6. Controlled variable under disturbances in heat load, using (a) fuzzy-PID and (b) conventional PID control.

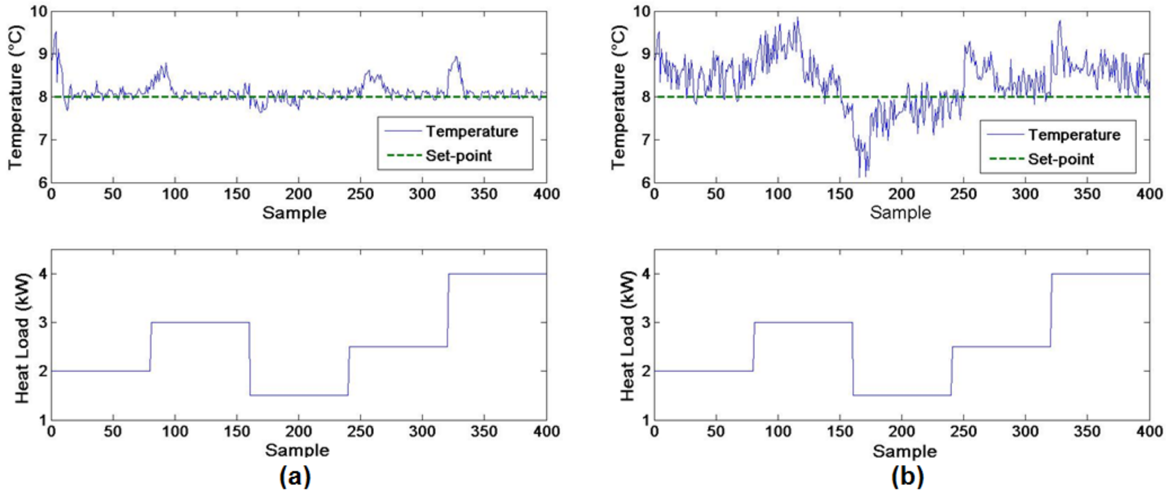

Figure 7. Controlled variable under disturbances in heat load, using (a) fuzzy-PID and (b) conventional PID control.

5. Conclusion

Stationary and dynamic behavior of an experimental refrigeration system was successfully reproduced by computational simulation. Using the developed model (ASPEN ® software) as a block in the Simulink-MATLAB environment, tests were carried out applying intelligent and classical controllers.

The open loop simulations showed a slightly nonlinear behavior for the studied plant, which explains the similar performance results around the steady state conditions for which the controllers were tuned.

The fuzzy controller also proved to be effective in controlling the system under different operating conditions. On the other hand, the classical controller was not able to consider the nonlinearity of the process, and the PID should be retuned for each new operating point.

From the results, it could be concluded that intelligent controllers might be preferable to the refrigeration system which presented nonlinear behavior mainly for set-point tracking purposes.

References

Consenza B., Galluzo M., 2011, Adaptive Type-2 Fuzzy Logic Control of Non-Linear Processes, Chemical Engineering Transactions, 24, 235-240, DOI: 10.3303/CET1124040.

Li H. X., Gatland H. B., 1996, Conventional fuzzy control and its enhancement, IEEE Transactions on Systems, Man, and Cybernetics, 26, 5, 791-797.

Pinelli T. G., 2008, Automation and analysis of the energy consumption of a cooling system for cooling a liquid, Thesis, School of Chemical Engineering, UNICAMP, São Paulo, Brasil (in Portuguese).

Schurt l. C., Hermes C. J. L., Neto A. T., 2010, Assessment of the controlling envelope of a model-based multivariable controller for vapour compression refrigeration systems. Applied Thermal Engineering, 30, 1538-1546.

Shaw I. S., Simões M. G., 1999, Control and Fuzzy Modeling), Edgard Blücher Editor, 1999, São Paulo, 2-14, 42-46, 63 (in Portuguese).