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DYNAMIC SIMULATION OF MULTI-COMPRESSOR FOOD RETAIL REFRIGERATION SYSTEMS

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ABASTRACT

This paper provides results of experimental investigations on the effect of on/off control parameters on the efficiency and stability of the control of multi-compressor refrigeration systems in retail food stores. The paper also reports on a simulation model that is being developed to enable the investigation of alternative control strategies and design options for supermarket refrigeration systems. The model is based on the TRNSYS simulation environment and considers the geometric characteristics of the components, controls and frosting on the evaporator coils. It can be employed for the investigation and comparison of alternative system control strategies such as, on/off and PID controls, and design options. The usefulness of the model is illustrated by comparing the performance of an on/off controlled multi-compressor refrigeration system with that of a system employing variable speed control on one of the compressors.

INTRODUCTION

Refrigeration is a major user of energy in the UK, accounting for around 17% of total electrical energy consumption [1]. It is estimated that supermarket refrigeration nation-wide, is responsible for the consumption of 9.2 x 10^6 kWh costing in excess of £480 million. A large proportion of this energy can be saved through better system component integration and control. Most current supermarket refrigeration systems employ multiple compressors connected in parallel and piped to common suction and discharge manifolds. This arrangement allows for capacity control, by means of on/off switching of the compressors in response to the desired suction pressure set-point [2]. On-off control is widely employed, due to its reliability and low cost. However, frequent on/off switching of the compressors is not desirable because short cycling results in abrupt changes in suction pressure and imposes severe stresses on the compressor [3]. This increases wear and tear of the compressor components and may finally lead to compressor failure. To avoid the disadvantages of on/off control and achieve better system efficiency more sophisticated control strategies should be investigated and utilized.

The application of microprocessor-based systems to the control of refrigeration plant in order to provide accurate temperature control of display cabinets has greatly improved in recent years. So much so, that the implementation of control strategies can be undertaken with ease. A number of strategies have evolved but in the majority of cases they still rely on the on/off switching of the compressors.

Better refrigeration system control and higher energy efficiencies can be achieved if compressor on/off control is replaced by variable speed control to closely match the variation in load using PID or more sophisticated control strategies based on predictive or `intelligent' schemes.

Full-scale experimentation on alternative control strategies can be disruptive and very expensive and the use of system simulation techniques provides an ideal vehicle for the investigation of alternative control strategies and design options for supermarket refrigeration systems. This paper presents results of simulation studies in the search for improved controls for multi-compressor supermarket refrigeration systems. The simulation results have been validated on a small scale experimental test rig in the laboratory.

EXPERIMENTAL REFRIGERATION SYSTEM

All validation experiments have been performed on a mini-supermarket refrigeration system in the laboratory. The system consists of two refrigerated display cabinets served by a mini multi-compressor pack. The instrumental display cabinet is situated an environmental chamber, which is fitted with an air handling unit and humidifier system to provide humidity and space temperature control.

The mini compressor pack is comprised of three unequal capacity DWM semi-hermetic compressors. Two Searle MDS twin fan air-cooled condensers are mounted at high level above the compressor pack and provide heat rejection to the ambient. The condensers are piped in parallel with each fan being switched independently, which gives a five-stage control of the condensing pressure. The refrigerant employed is R22 and its mass flow rate is measured using a Coriolis mass flow meter. The power consumption of the compressors is recorded using a 'Prime' series 500 power transducer.

The control system is comprised of a central network 'Supervisor', which is capable of controlling or monitoring two networks of up to 32 controllers or pressure/temperature transducers on each network. The controller switches compressors on or off in response to the rise or fall of pressure in the suction line. Setting up the controller requires the selection of four parameters, the target suction pressure, a pressure differential, a stage skip and a time delay.

The performance of the system is monitored by a computer-based data logging system, which logs pressures, temperatures, flow rates, and power consumption at regular intervals. More details on the test rig and data logging system have been reported by Chan and Tassou [4].

MODEL DESCRIPTION

The model developed for the above laboratory refrigeration system is based on the TRNSYS simulation environment. TRNSYS provides the capability to construct system models based on developed component models and a specification of the interconnecting piping.

The model is organised functionally into two major sections. The first section combines the compressors, condensers, and thermal expansion valve routines into an interrelated high-side unit. The second section, the low side unit, contains the evaporator model. The calculations proceed iteratively between these two sections until the desired overall thermal balance is obtained. A control subroutine, which couples together these two sections, can simulate different control schemes and operating strategies. The supply air parameters for the condenser and evaporator are time dependent to facilitate the simulation of the effect of the variation of ambient and space conditions. Input parameters to the system model include:

- the level of evaporator exit superheat (or quality),
- the level of required condenser sub-cooling (or quality),
- time dependent condenser and evaporator inlet air parameters,
- dimensions of components and interconnecting piping
- control scheme for the system
- starting and stopping times and time step for the simulation .

To increase the speed of simulation and facilitate convergence, some initial estimates of parameters need to be provided as follows:

- the refrigerant temperature at the evaporator inlet,
- the refrigerant saturated temperature at the condenser inlet,
- input control functions for compressors and condenser fans.

These above three estimates are used as starting points for the iterations. The final results are independent of the initial estimates, but good initial estimates result in shorter running times. Two methods of solution can be employed.

One relies on the refrigerant flow balance across the compressor and the expansion device and requires detailed modelling of the expansion valve whereas the other relies on the achievement of the required degree of superheating and subcooling irrespective of the type of expansion device employed.

Outputs from the model include:

- the instantaneous suction and condensing pressures
- the cooling capacity and compressor power consumption of the system
- the state of the refrigerant (pressures and temperatures) at various points in the cycle.

Compressor model

Since the compressor is the heart of the refrigeration system and the primary user of electrical power, accurate compressor modelling is important to good system performance prediction. However, a complex compressor model requires detailed hardware design parameters, which are not system specific and not easy to obtain from the manufacturers. In the present study, a fairly simple compressor model has been employed which is based on loss and efficiency terms. This model has been calibrated using data from experimental results from compressor tests in the laboratory.

Heat exchanger models

The air-to-refrigerant condenser and evaporator models have been developed based on the:

- effectiveness vs. Ntu correlation for heat transfer of a dry coil,
- a modified version of the enthalpy different approach when there is dehumidification.

The two heat exchanger models are similar apart from the dehumidification algorithm employed for the evaporator model. The calculation methods used assume that the heat exchangers consist of equivalent, parallel refrigerant circuits with unmixed flow on both the air and refrigerant sides. For each circuit, the refrigerant-side calculations are separated into computations for the superheated and two-phase regions for the evaporator and for the superheated, two-phase, and sub-cooled regions for condenser.

As a part of the whole system simulation for supermarket energy, the heat exchanger models are founded based on lump method. In this case, the heat transfer for the liquid, vapor, and two-phase refrigerant regions of the heat exchanger are computed using effectiveness vs. Ntu correlation, except for the two refrigerant regions of evaporator with dehumidification and frosting [5][6].

Most supermarket refrigeration systems operate under frost conditions for the majority of time so modeling of frost formation is an important consideration in an overall system simulation model. Frost formation on evaporator coils has a number of influences on the performance of refrigeration systems which include: increase in the total thermal resistance of the coil, decrease of the air flow rate, and eventual reduction of the operating efficiency of the system. The thermal resistance of frost layer and airflow rate are both dependent on the frost thickness, the density of the frost layer, and the system running time. These variables make the performance of the coil time dependent. The requirement for periodical defrosting necessitates the on/off cycling of the compressors alongside the cycling performed to maintain the suction pressure constant during normal operation. To obtain, therefore, realistic system simulation results the dynamic frosting process on the evaporator coil should be taken into account in the evaporator model. The present model utilizes a semi-empirical correlation developed by Malhammar [7] [8] [9] to model the effect of frost formation on system performance.

Control model

To achieve the required evaporating temperature and stability in system operation, the suction and discharge pressures of multi-compressor supermarket refrigeration systems are normally controlled at pre-set values by cycling the compressors and the condenser fans on and off in response to changes in the suction and discharge pressure respectively.

In the model a control subroutine has been developed which emulates the control strategy employed in the control of standard supermarket refrigeration systems.

Thermodynamic properties

The refrigerant properties are calculated using subroutines from the NIST software package REFPROP [10]. REFPROP can calculate the properties of a large number of pure fluids and up to five component-mixtures of these fluids.

Model validation

Comparisons between measurements with on/off control and corresponding model predictions were made to determine the accuracy and limitations of the quasi-steady state model.

Figures 1 and 2 present a comparison between the actual and simulated suction and discharge pressures. It can be seen that the model is able to trace quite accurately the overall variation in the suction and discharge pressures arising from the on/off switching of the compressors and condenser fans. Close examination of Figure 2 reveals that even though the average experimental discharge pressure is very close to that obtained from the model, the actual response of the discharge pressure from fan switching is faster than the model response. This discrepancy requires further investigation.

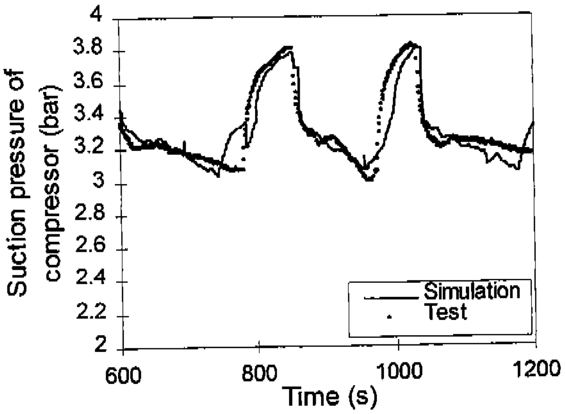

Figure 1. Comparison of simulation with test for suction pressure of compressor

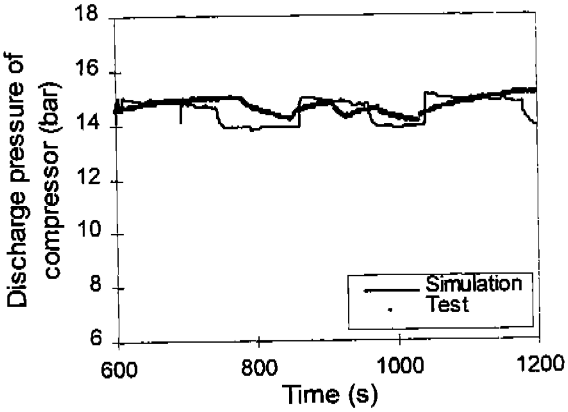

Figure 2. Comparison of simulation with test for discharge pressure of compressor

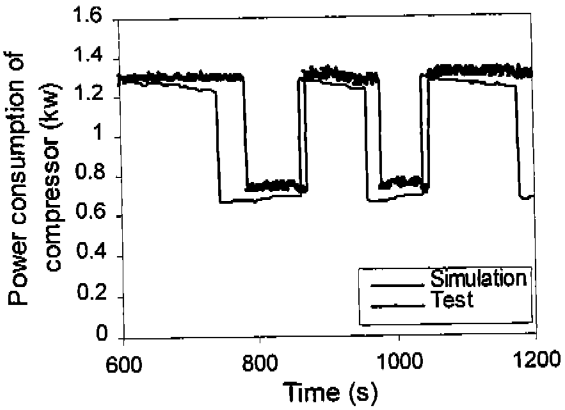

Figure 3. Comparison of simulation with test for power consumption of compressor

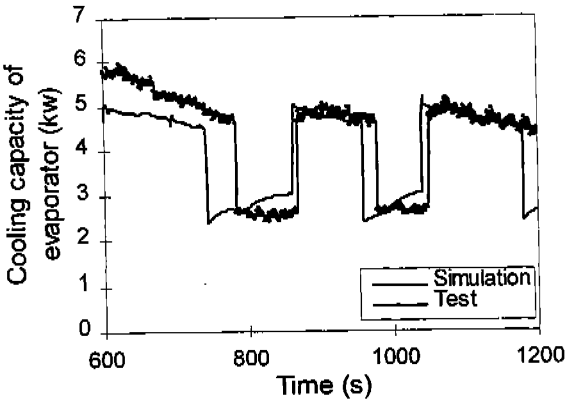

Figure 4. Comparison of simulation with test for cooling capacity of evaporator

Figure 3 presents a comparison between the power consumption obtained from the experiments and that predicted by the model. It can be seen that the model predicts quite well the maximum compressor power consumption as well as the variation of the power arising from compressor cycling. There is a small difference between the time that one of the compressors remains switched off between cycling and this could be due to a number of reasons such as underestimation of the effect of frosting on the response of the evaporator. This is also evident from the discrepancy between the experimental and model response for the cooling capacity of the evaporator illustrated in Figure 4.

The developed model can be used to investigate the effect of different control strategies on the primary control variable which is the suction pressure and the overall energy consumption of the system. A possible strategy is the application of variable speed control on one of the compressors.

The simulation results for such a strategy are shown in Figures 5 to 7. Figure 5 presents the variation of suction pressure which as can be seen is much more uniform than the suction pressure achieved with on/off control (Figure 1). The variable speed control also results in a lower compressor power consumption as illustrated in Figure 6. Figure 7 shows that a variable speed system will produce a lower but much more uniform cooling at the evaporator which will result in a much more stable operation and reduced frost accumulation rates.

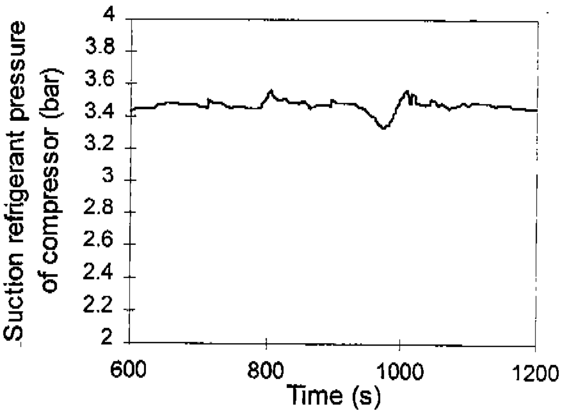

Figure 5. Simulated refrigerant suction pressure with variable speed control

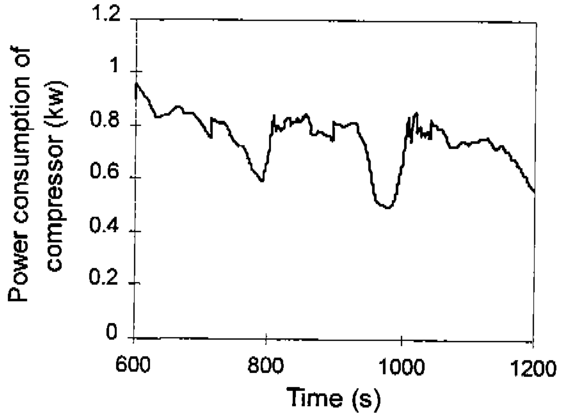

Figure 6. Power consumption of compressor with variable speed control

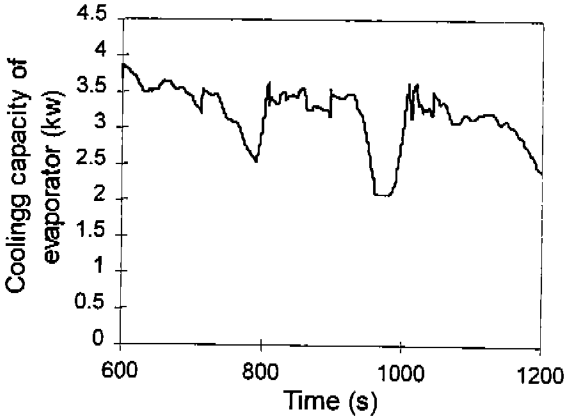

Figure 7. Cooling capacity of evaporator with variable speed control

CONCLUSIONS

This paper presented a model for the simulation of multi-compressor supermarket refrigeration systems based on the TRNSYS simulation environment. The model has been validated using experimental results from the laboratory and has shown to perform reasonably well. Control subroutines have been used to simulate the control philosophy of conventional on/off control systems and the flexibility and usefulness of the model has been illustrated by demonstrating the effect of implementing variable speed control on one of the compressors. The model will be developed further to allow the seasonal simulation and facilitate comparison between alternative refrigeration and environmental control systems for retail food stores.

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