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SIMULATION-BASED AUTOMATED COMMISSIONING METHOD FOR AIR-CONDITIONING SYSTEMS AND ITS APPLICATION CASE STUDY

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ABSTRACT

This paper proposes an automated commissioning method for air-conditioning systems through comparing the measured energy consumption with the simulated energy consumption, which is simulated using a model newly developed through fitting manufacturer's specification data. This commissioning method is verified using a Gas-engine Heat Pump (GHP) air-conditioning system. The results show that this method can verify whether a real air-conditioning system is performing in conformity with the design intent or not. Finally a commissioning case is studied using the commissioning method proposed here.

INTRODUCTION

Since the Energy Crisis caused by the Middle East War in 1973 to 1974, the urgent need for oil security management and energy policy co-operation led to the establishment of International Energy Agency (IEA) and comprehensive study on energy efficiency (Scott, 1994). In the field of building energy conservation, many Energy Conservation Measures (ECM) were developed and used in the buildings participating in the energy conservation program. However some analyses on the data from these buildings revealed that many of the installed energy efficiency measures were not performing as expected (Bonneville Power Administration, 1992). Therefore the idea that commissioning is a viable method to help ensure good performance of buildings and their ECMs was gradually conceived since 1989.

Building commissioning is the process of ensuring that systems are designed, installed, functionally tested, and capable of being operated and maintained to perform in conformity with the design intent (ASHRAE, 1996).

However building commissioning is a time and cost-consuming work because there are too many types of equipment and component in an air-conditioning system should be verified. Furthermore, the verification check and functional performance test should be conducted under a wide range of load conditions. Therefore to reduce commissioning cost and time is an urgent problem to solve. Automating commissioning progress is a viable way to reduce commissioning cost and time. Simulation is considered to be a powerful tool to automate commissioning progress because it can give the performance of a building and its systems matching the design intent (Wang and Yoshida, 2003). The simulation-based commissioning for many types of components or subsystems in a Heating, Ventilation and Air-conditioning (HVAC) system has been studied. For example, Wang et al. (2003) proposed a model-based commissioning method for fan subsystems. Miyata et al. (2004) studied how to commission Variable Air Volume (VAV) unit using statistical method and dynamic system analysis. The research of using simulation in commissioning process can also been found about Air Handling Units (Erikson, 2003), chilling plant (Georges and Lebrun, 2004), coil energy recovery Loop systems (Erikson, 2004), duct system (Odajima et al., 2004), and filter in room air-conditioners (Wang et al., 2004). However the simulation-based commissioning for multi-condenser/evaporator air-conditioning system has not yet be studied. This paper focuses on developing an automated commissioning method for multi-condenser/evaporator air-conditioning systems through comparing the measured energy consumption with the simulated energy consumption.

The key components of an automated commissioning tool should include a set of models suitable for commissioning, a set of test sequences, and software to implement the test sequences and to analyze data to give commissioning recommendation (Annex 40, 2004). This paper firstly describes the energy consumption estimation model newly developed through fitting manufacturer's specification data. Based on this model, the performance in conformity with design intent can be simulated and used to check whether the real performance matches design intent or not. Finally using this simulation-based commissioning method, a case study is introduced, which is the commissioning for a multi-evaporator/condenser Gas-engine Heat Pump (GHP) air-conditioning system.

SIMULATION MODEL

Model description

The simulation model should be developed using manufacturers' specification data because the specification data is measured under the conditions of equipments running fault-freely, which represent the performance in conformity with design intent. Through comparing the simulated performance using this kind of model, the verification check can be realized that whether an air-conditioning system is performing in conformity with design intent or not.

For an air-conditioning system, the manufacturers' specification performance is described using the energy consumption under different load conditions. An example specification table is shown in Table 1. As shown in Table 1, three variables influence the air conditioner's energy consumption, i.e. outdoor air dry-bulb temperature, indoor air wet-bulb temperature, and cooling amount produced by the air conditioner. Therefore this paper uses a three-variable square equation to simulate the energy consumption of an air-conditioner, as shown in Equation 1.

The coefficients in Equation 1, i.e. a_i, b_i, c_i, d, $i=1,2,3$, can be determined using least square difference method. That is, given inputs T_o, T_i, CA, and the output RE from specification data, find coefficients a_i, b_i, c_i, d, $i=1,2,3$ that "best-fit" the Equation 2. The Levenberg-Marquardt method (More, 1977) can be used to solve this non-linear data-fitting problem.

Model parameters, inputs and output

The model parameters are the coefficients of a_i, b_i, c_i, d, $i=1,2,3$, which are fitted using manufacturer's specification data. The inputs to the model are outdoor air dry-bulb temperature T_o, indoor air wet-bulb temperature T_i, and the cooling amount CA produced by the air-conditioner. The output is the ratio of energy consumption to nominal capacity.

Model validation

The model accuracy is checked through modeling an example air-conditioner's specification data. The example air-conditioner performance data shown in Table 1 are used to fit the coefficients in Equation 1.

Because the specification data given by the manufacturer do not include the performance data of cooling amount lower than 50% of nominal capacity, the coefficients fitting is divided into two parts, one of which is the cooling amount is lower than 50% of nominal capacity and the other is the cooling amount is larger than 50%. At the part of lower than 50% of nominal capacity, the energy consumption is estimated using a linear relation between cooling amount and energy consumption according to the recommendation of the manufacturer, i.e. the coefficient of a_3 in Equation 1 is assumed to be zero.

Table 1
Example of an air conditioner's specification data

INDOOR AIR WET-BULB TEMPERATURE (^oC)	**16.0**		**18.0**		**19.0**		**20.0**		**22.0**		**24.0**	
OUTDOOR AIR DRY-BULB TEMPERATURE (^oC)	**CA (kW)**	**RE**	**CA (kW)**	**RE**	**CA (kW)**	**RE**	**CA (kW)**	**RE**	**CA (kW)**	**RE**	**CA (kW)**	**RE**
25.0	33.4	0.77	37.2	0.87	39.1	0.92	39.5	0.93	40.5	0.96	41.5	0.99
27.0	32.6	0.79	36.4	0.89	38.4	0.94	38.8	0.95	39.8	0.98	40.8	1.00
29.0	31.9	0.82	35.7	0.91	37.7	0.95	38.1	0.97	39.1	0.99	41.1	1.02
31.0	31.2	0.84	35.0	0.93	36.9	0.97	37.4	0.98	38.4	1.01	39.4	1.04
33.0	30.5	0.86	34.3	0.94	36.2	0.98	36.7	1.00	37.7	1.02	38.6	1.05
35.0	29.8	0.88	33.6	0.96	35.5	1.00	36.0	1.01	36.9	1.04	37.9	1.07
37.0	29.1	0.89	32.9	0.97	34.8	1.02	35.3	1.03	36.2	1.06	37.2	1.08
39.0	28.4	0.91	32.2	0.99	34.1	1.03	34.6	1.05	35.5	1.07	36.5	1.10

$$RE = (a_1 T_o^2 + b_1 T_o + c_1)(a_2 T_i^2 + b_2 T_i + c_2)(a_3 CA^2 + b_3 CA + c_3) + d \qquad (1)$$

$$\begin{aligned} &\min \frac{1}{2} \left\| (a_1 T_o^2 + b_1 T_o + c_1)(a_2 T_i^2 + b_2 T_i + c_2)(a_3 CA^2 + b_3 CA + c_3) + d - RE \right\|_2^2 \\ &= \min \frac{1}{2} \sum_j [(a_1 T_{o,j}^2 + b_1 T_{o,j} + c_1)(a_2 T_{i,j}^2 + b_2 T_{i,j} + c_2)(a_3 CA_j^2 + b_3 CA_j + c_3) + d - RE_j]^2 \end{aligned} \qquad (2)$$

The coefficients fitting results are shown in Table 2. The ratios of energy consumption to nominal value are calculated using the fitted model and compared with the specification data. The model accuracy is evaluated using Root Mean Square Difference (RMSD) between model estimated data and specification data. The RMSD is calculated using Equation 3 and the relative RMSD is calculated using Equation 4. The RMSD and maximum and average relative RMSD are shown in Table 2. The average relative RMSD is 1.73% for the data of 0~50% of nominal capacity and is 3.11% for the data of more than 50% of nominal capacity, which show that the model is accurate enough for commissioning an air-conditioner. Figure 1 shows a visual correlation between model estimated energy consumption ratios and the specification values. From Figure 1 it can be found that the model estimation data match the specification data well and good accuracy can be seen.

$$RMSD = \sqrt{\frac{\sum_{i=1}^{n}(RE_m - RE_s)^2}{n}} \quad (3)$$

$$RRMSD_i = \frac{RMSD}{RE_{s,i}} \quad (4)$$

Table 2
Model fitting results of an example air conditioner

	0~50% OF NOMINAL CAPACITY	**>=50% OF NOMINAL CAPACITY**
a_1	2.4361E-04	3.8841E-04
b_1	-1.0408E-02	4.7352E-03
c_1	5.5889E-01	6.9613E-01
a_2	-6.9480E-06	2.8467E-04
b_2	-2.2386E-03	-1.2641E-02
c_2	4.3479E-01	3.8456E-01
a_3	0.0000E+00	2.0340E-04
b_3	1.4616E-01	7.5236E-02
c_3	4.8470E-02	-5.5769E-01
d	-9.0574E-03	2.2280E-01
RMSD	0.0085	0.0221
Maximum RRMSD	2.436%	6.318%
Average RRMSD	1.729%	3.112%

COMMISSIONING METHOD

The automated commissioning for an air-conditioning system can be achieved through comparing the real-time performance with the performance simulated using the model proposed by this paper. If the difference between real-time performance and simulated performance exceeds a predetermined threshold (20% of model estimation

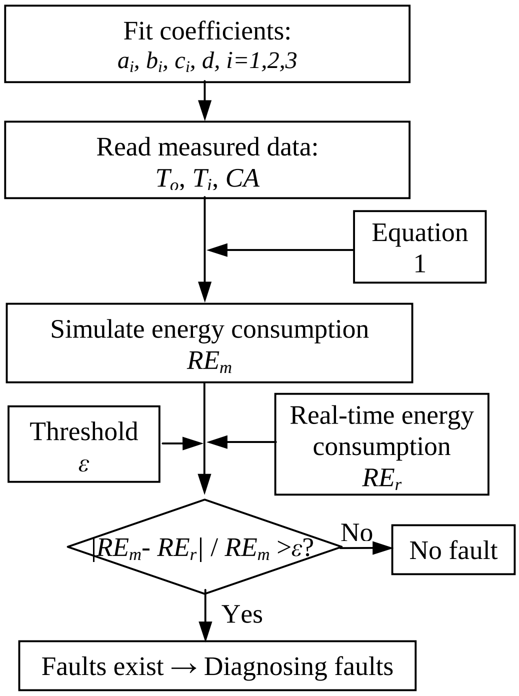

Figure 2 Flow chart of automated commissioning for air-conditioning systems

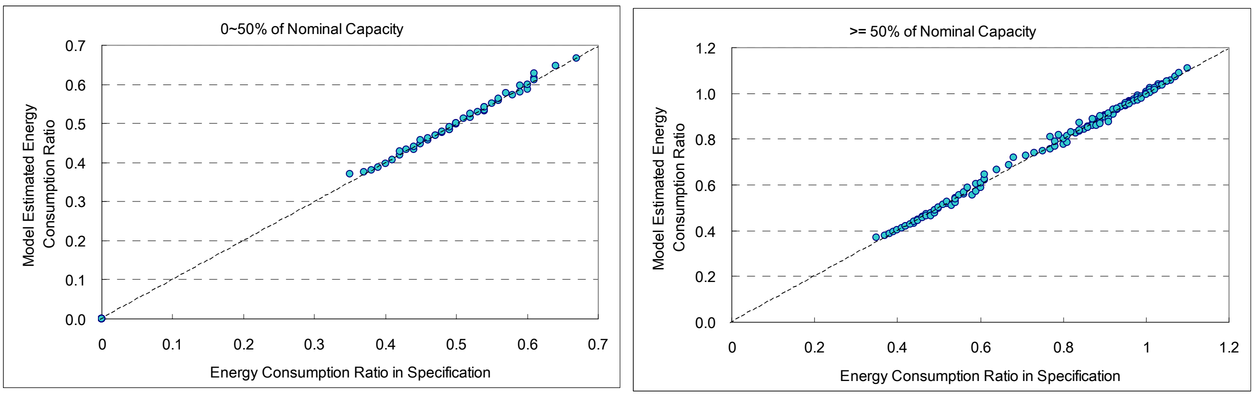

Figure 1 Model accuracy verification results

value is recommended according to the authors' experience), the air conditioning system can be concluded that it is not performing in conformity with design intent, which implies some fault might exist and fault diagnosis is necessary. The following procedure shows how to achieve automated commissioning using this model.

1) Fit the coefficients in Equation 1.

2) Input the real-time outdoor air dry-bulb temperature T_o, indoor air wet-bulb temperature T_i, and the cooling amount produced by the air-conditioner *CA* to the model to simulate the fault-free performance.

3) Compare the simulated performance with real performance to verify whether the air-conditioning system is running in conformity with design intent.

Figure 2 shows the flow of using the commissioning method.

COMMISSIONING CASE STUDY

Simulation-based performance check

This paper studied a case of commissioning a multi-evaporator/condenser GHP air-conditioning system using the commissioning method proposed by this paper. The air-conditioning system consists of an outdoor unit and four indoor units. Its profile is shown in Table 3. The air conditioning system plan configuration is shown in Figure 3.

The real performance was compared with simulated performance to check whether the performance of the air-conditioning system match the specification performance or not. Figure 4 shows the comparison results for a typical summer day. The maximum and average differences between measured and simulated Liquefied Petroleum Gas (LPG) consumption are 209.3% and 45.9% of the simulated value. These large differences show that there must be some fault that is influencing the operation of the air-conditioning system. The following parts describe the diagnosis for the system and performance improvement recommendation.

Table 3 Profile of the commissioned air-conditioner

Commissioned building name	R&D Center, Yanmar Co. LTD.
Air-conditioner type	GHP YNZP355F1
Heating/cooling capacity (kW)	42.5/35.5
Rated LPG consumption (heating/cooling, kW) (LPG HHV=90.27MJ/Nm^3)	28.0/28.5
Refrigerant	R407C
Outdoor unit rated power (kW)	1.09
Outdoor unit fan rated air flow rate (m^3/min)	230
Indoor unit number	4
Indoor unit rated power (W)	30
Indoor unit fan rated air flow rate (high/low speed, m^3/min)	20/15

Fault diagnosis

In order to find the reasons why the real performance deviated so much from the specification performance, the air-conditioning system was measured in detail, i.e. refrigerant flow rate, condensing and evaporation pressure and temperature, and LPG consumption. The refrigeration cycle state points definition is shown in Figure 5 and the refrigerant-flow chart of the air-conditioning system

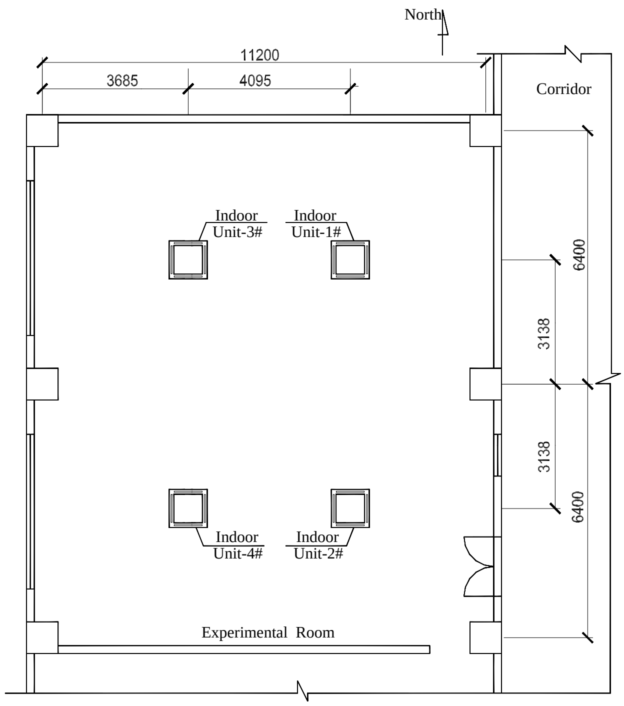

Figure3 Air-conditioning system plan

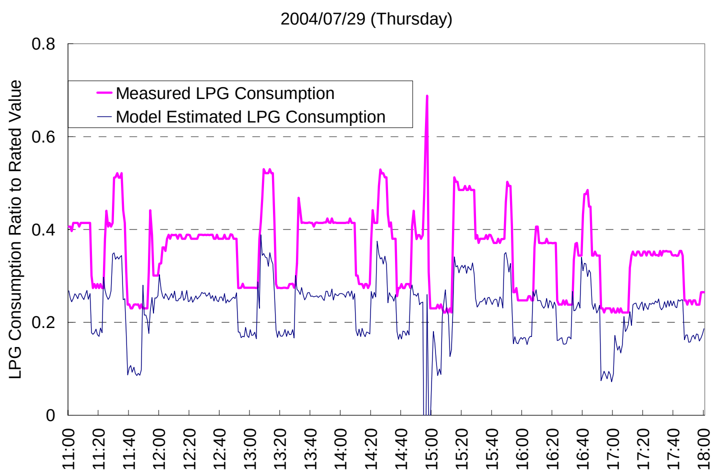

Figure 4 Comparison of real performance with simulated performance

and the measurement points are shown in Figure 6. The measurement items and measurement place are shown in Table 4. The refrigerant property calculation software REFPROP (NIST 2002) is used to calculate refrigerant density and enthalpy given refrigerant composing substance, pressure and temperature.

Figure 7 shows the meteorological data and measured cooling amount produced by the air-conditioning system on the typical summer day. From the figure it can be observed that the highest outdoor air temperature on that day was about 35^{o}C, which was quit a hot day. However the cooling amount produced by the air-conditioning system is about 8.4 kW, which is only 20% of the nominal capacity 42.5 kW. This means even during the hottest summer days, only 20% of the air-conditioning system nominal capacity can fulfill the cooling demand of conditioning the air in the room. Therefore it can be

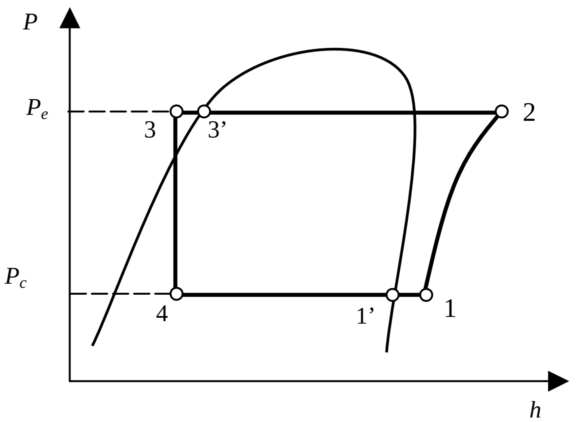

Figure 5 Refrigeration cycle and state points definition

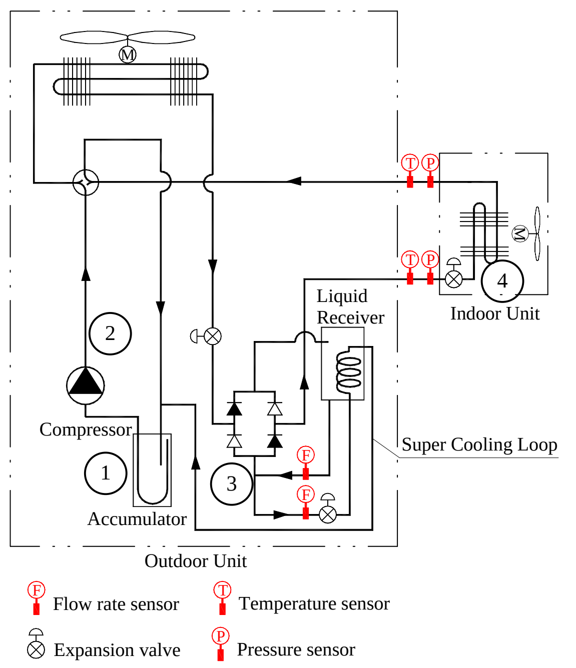

Figure 6 Flow chart and measurement points

conclude that the air-conditioning system is over-sized. This makes the air-conditioning system always run at low-load condition, which generally causes low energy efficiency.

Improvement measure

Since the reason for the low energy efficiency is caused by the low cooling load, a measure to make the air-conditioning system run at high cooling load conditions is proposed to improve its performance. Because the four indoor units are used to condition the air in one big room, it is reasonable to make the four units to run and stop simultaneously. So the air-conditioning system can run at high cooling load conditions periodically instead of running at low-load conditions continuously. This control algorithm was introduced to the air-conditioning system and the performance of indoor units simultaneous operation was measured. The measurement results are shown in Figure 8. From this figure it can be found that the measured LPG consumption matched the simulated value quite well. The difference between average measured and simulated LPG consumption is 3.62% of simulated value. This result shows that this improvement measure can improve the air-conditioning system's energy performance and make it run in conformity with specification performance.

Discussion on simultaneous and individual operation

Table 4 Measurement points for the commissioning

Measurement items	Measurement place
Total refrigerant flow rate	Outlet of liquid receiver.
Super cooling Refrigerant flow rate	Super cooling loop
Evaporation pressure & temperature	Outlet of indoor unit
Condensing pressure & temperature	Before expansion valve
LPG consumption	Gas supply pipe

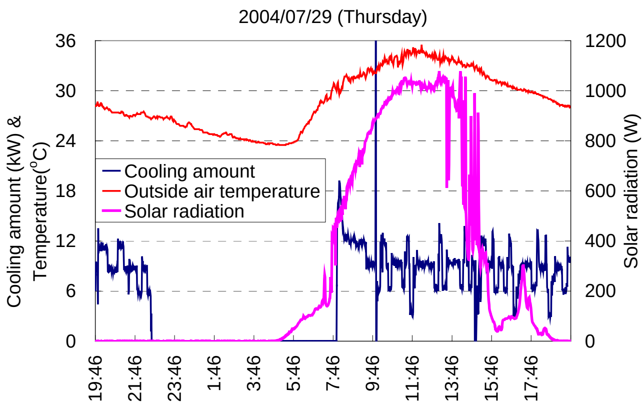

Figure 7 Meteorological data and cooling amount on the typical summer day

In order to investigate the reasons why the energy performance of the air-conditioning system at low-load conditions is inefficient, the performance of all indoor units simultaneous operation is compared with the individual operation on two days with similar cooling load conditions. The simultaneous operation is carried out on September 4th and the individual operation is carried out on September 19. Figure 9,10, and 11 show the comparison of cooling load, LPG consumption and refrigerant flow rate on the two days respectively.

From Figure 9 it can be found that the sum of cooling amount on the two days is similar, which shows that the thermal conditions of the two days were similar.

However the sum of LPG consumption of individual operation is two times of simultaneous operation, as shown in Figure 10.

Figure 11 shows the total refrigerant flow rate, the super-cooling refrigerant flow rate and the sum of the refrigerant flow of two operation modes. The sum of the refrigerant flow of individual operation is 1.45 times of simultaneous operation. The sums of the cooling amount on the two days are similar, but the sum of refrigerant flow of individual operation is more than that of simultaneous operation. This means that in order to produce same cooling amount as simultaneous operation, the individual operation needs to deliver more refrigerant. This is why the individual operation consumes more energy. The reason why individual operation needs to deliver more refrigerant to produce same cooling amount can be summarized from Figure 11. From Figure 11, it can be observed that the super-cooling refrigerant flow rate of individual operation is larger than that of simultaneous operation. The sum of super-cooling refrigerant flow of individual operation is 292.85 liter more than that of simultaneous operation. Meanwhile the sum of total refrigerant flow of individual operation is 273.96 liter more than that of simultaneous operation, which is almost equal to the difference of super-cooling refrigerant flow between simultaneous operation and individual operation. This shows that all the amount of the refrigerant that was more delivered by individual operation was cycling in the super-cooling loop.

Because the engine-driven compressor’s rotational speed cannot be reduced to smaller than the minimum value, generally 50% of the nominal value, under low load conditions refrigerant flow rate fewer than 50% of nominal flow rate cannot be realized. The part of refrigerant flow more than necessary is

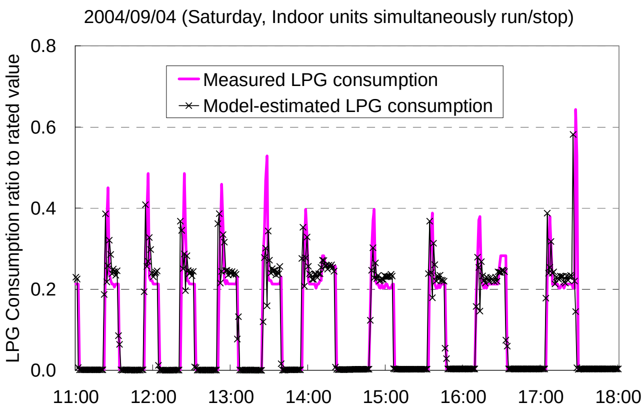

Figure 8 Measured performance of the simultaneous operation compared with simulated performance

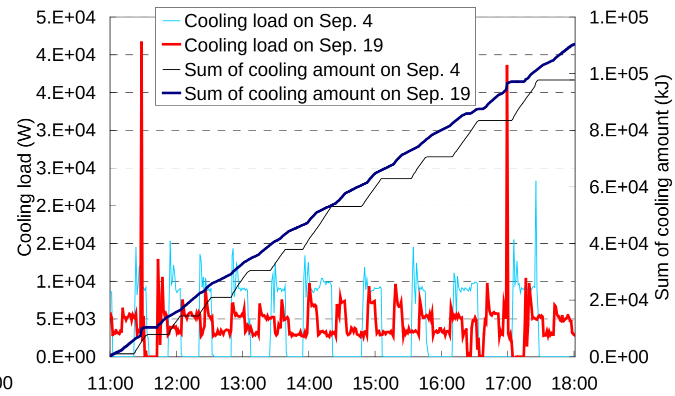

Figure 9 Comparison of cooling load on the two days of simultaneous operation and individual operation

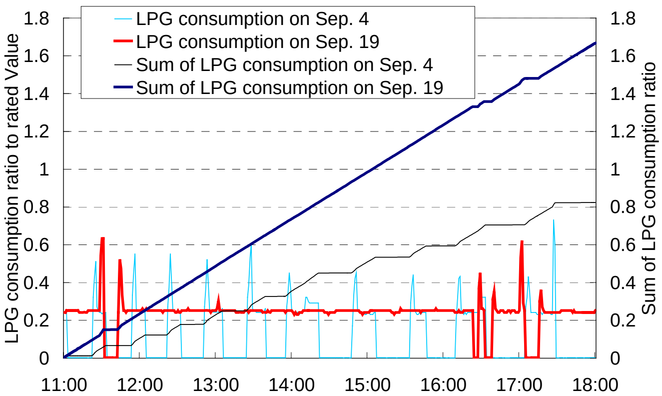

Figure 10 Comparison of LPG consumption on the two days of simultaneous operation and individual operation

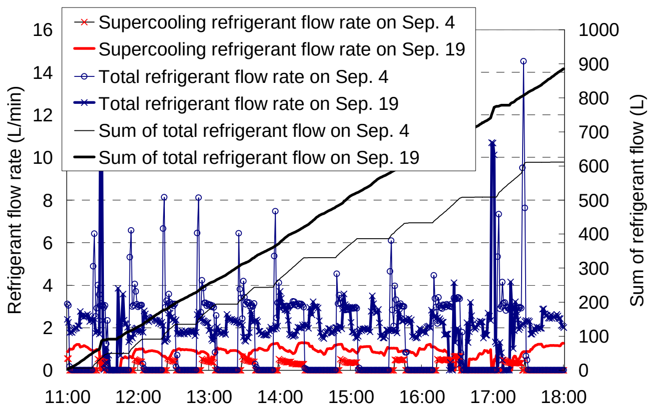

Figure 11 Comparison of refrigerant flow rate on the two days of simultaneous operation and individual operation

cycling through a bypass loop, super-cooling loop. This is why the air-conditioning system energy efficiency is low during low load operation.

Disadvantage of simultaneous operation

Although the measure of running all the indoor units simultaneously can improve the energy efficiency of an air-conditioning system, the following two aspects of disadvantage cannot be ignored.

1) The issue of the on/off frequency

Because all the indoor units run simultaneously, the cooling amount produced under this operation mode is larger than that of individual operation mode. When the cooling load is low, the system run by simultaneous operation mode will switch on/off more frequently than that of individual operation. This might influence the span of the life cycle of an air-conditioning system. The life of air-conditioning systems is generally expressed using running-hours and on/off times. The value of running-hours divided by on/off times can be used as a threshold to determine whether the on/off frequency is acceptable or not. If the on/off time interval of an air-conditioning system under simultaneous operation mode is longer that the threshold, the simultaneous operation is acceptable and will not reduce the life span of the system compared with individual operation.

2) The issue of indoor thermal comfort

Although it is reasonable to run the simultaneous operation mode for the indoor units in one big room, the problems related to thermal comfort might be caused if the cooling load situations are not uniform enough, for example the cooling load situations of perimeter zone and interior zone might differ much. Because this operation mode runs and stops all the indoor units simultaneously, the air-conditioning system will start or stop only according to one thermostat. So only the temperature of the zone where the thermostat exists can be control accurately. The thermal environment of the other zones where the thermostat does not exist might exceed the comfort range if the heat gain is not similar to the zone where the thermostat exists.

CONCLUSION

This paper proposes a method for automatically commissioning air-conditioning systems through simulating the fault-free performance of the systems using a newly developed model. The model is a regression one obtained by fitting the air-conditioning system's specification data. The model coefficients fitting achieved good fitting accuracy that the relative RMSD is less than 6.32%.

The commissioning method is verified using a case study. The average LPG consumption of the air-conditioning system for case study was 45.9% more than the specification performance, which implies that faults exits in the air-conditioning system. The fault diagnosis was carried out and the results show that the reason is the air-conditioning system was over-sized. An improvement measure was proposed, which is to run all the indoor units simultaneously. The measurement results show that this method can improve the air-conditioning system's energy efficiency and make the system run in conformity with the specification performance.

The disadvantage of this simultaneous operation mode is that it might increase the on/off frequency of an air-conditioning system or might decrease the system's life span and it might cause the problem of thermal comfort if the load situations are not uniform enough in a large room.

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NOMENCLATURE

a_i, b_i, c_i, d, $i=1,2,3$ – Coefficients fitted using manufacturer specification data
CA – Cooling amount produced by air-conditioner
HHV – High heat value, (MJ/Nm^3)
LPG – Liquefied petroleum gas
RE – Ratio of energy consumption to nominal value
RMSD – Root mean square difference
RRMSD – Relative root mean square difference
T_i – Indoor air wet-bulb temperature (^oC)
T_o – Outdoor air dry-bulb temperature (^oC)

Subscriptions

m – Model estimated data
r – Real-time data
s – Specification data