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The energy efficiency monitoring of a refrigeration unit

Abstract

In the paper, a monitoring system of a refrigeration unit is presented. This system consists of several measurement elements e.g. (pressure, temperature, energy, etc. sensors) connected using a serial RS485 network. A measurement level is a source of data for both SCADA environment and a PLC controller which are essential elements of the whole control system. The first stage of the study was related to the selection of measurement devices and a construction of a serial network. The authors also described how to link a serial 485 network with a PLC controller and how to introduce it into TCP/IP network. In the first part of the paper, there is presented a refrigeration unit as a subject of the monitoring. Then the authors describe a theoretical background needed for the energy efficiency calculation. After that the system structure with selected details about hardware integration and SCADA software implementation is presented. The final part contains selected real time experiments to show typical working modes of the refrigeration unit and to prove the efficiency of the developed monitoring system.

Keywords: refrigeration unit, SCADA system, energy efficiency.

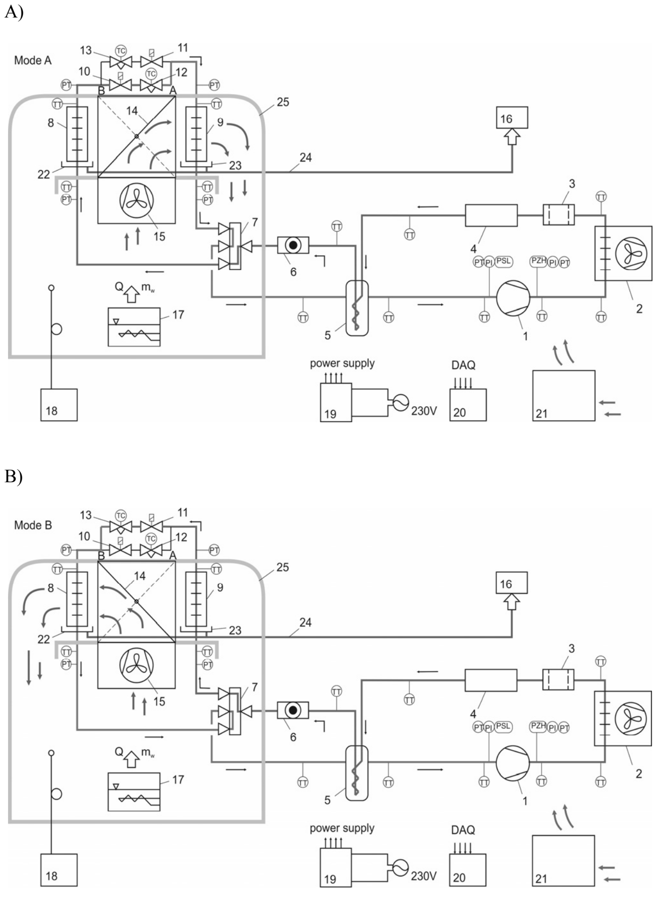
1. Introduction

Refrigeration and air conditioning systems consume approximately 15% of global energy [6]. Improvement in the energy efficiency in refrigeration is analyzed in many papers [1], [6], as inefficient use of energy contributes to the wasting of valuable resources.

Generation of low temperature heat (cold), with a temperature level below the ambient, requires energy to drive a refrigerating unit. A (useless) side effect of this process is the dew condensation and/or frosting of water vapor from moist air on the surface of air coolers operating at temperatures below the dew point and/or freezing. In addition, while operating at temperatures below freezing, air coolers must be defrosted periodically in order to restore their performance. Apart from a few exceptions, the majority of defrost systems e.g. electric, hot gas, reverse cycle, require additional energy to remove the frost [7]. Hence, the energy is consumed twice or even triple: when the frost forms, at its disposal, and the redistribution of heat delivered during defrosting. One way to improve the effectiveness and to reduce the drawbacks of defrosting is the recuperation of cold [5]. This paper presents experimental apparatus for the real-time monitoring of a refrigeration unit with recuperation of cold accumulated in the frosted air cooler. Directions of current research are also outlined.

2. General description of a refrigeration unit

A schematic diagram of a device using the frost accumulated on the cooler surface to heat recovery is shown in Figure 1. Heat exchangers (8) and (9) may change roles as the evaporator and the subcooler thanks to switching a four-way valve (7) and a damper (14). When the evaporator (9) has to be defrosted, the four-way valve (7) switches the direction of refrigerant flow. The device, after changing the organization of air traffic by moving the sequence damper (14) from position A to position B, will continue to refrigerate the cooling chamber interior, using the heat exchanger (8) as the evaporator. The cold accumulated in a frosted heat exchanger (9) (included in the temperature difference of the masses, the heat of frost melting and water evaporation) allows the subcooling of liquid refrigerant. Subcooling, occurring as a result of the recovery of cold, leads to an increase in the refrigeration capacity and the coefficient of performance. Additional advantages are the elimination of the adverse effects of standard defrosting and no interruption in cooling the interior of the chamber.


A)

B)

Fig. 1. Schematic diagram of the test stand with heat recovery from the frost– mode A and B: 1-compressor, 2-condenser, 3-drier, 4-flow meter, 5-suction accumulator, 6- sight glass, 7-four-way valve, 8,9-evaporator/subcooler, 10,11-solenoid valve, 12,13-expansion valve, 14-damper, 15-fan, 16-scale; 17-heater/steam generator, 18-electronic control device, 19-power supply with energy meters, 20- data acquisition system, 21-air conditioner, 22,23-drip tray, 24-drain line, 25-cold chamber

The test stand allows measuring all relevant parameters of a refrigeration unit. Based on the results of measurements, the refrigeration capacity (Q_o) and the coefficient of performance (COP) are determined:

- refrigeration capacity (Q_o)

$$Q_o = \dot{m}_r \cdot q_o \text{ , in kW} \tag{1}$$

where: $\dot{m}_r$ - mass flow rate of the refrigerant, kg/s; q_o - difference of specific enthalpy of refrigerant on the inlet and outlet of the evaporator, kJ/kg, determined with Refprop [5] on the basis of pressure and temperature measurement.

- coefficient of performance (COP)

$$COP = \frac{Q_o}{P} \text{, dimensionless} \tag{2}$$

where: P - compressor power consumption, kW.

3. Development of a monitoring and control system

A typical control system with monitoring functions consists of three elements shown in Figure 2. They are: a PLC controller, a network infrastructure (both serial and Ethernet types) and an HMI station.

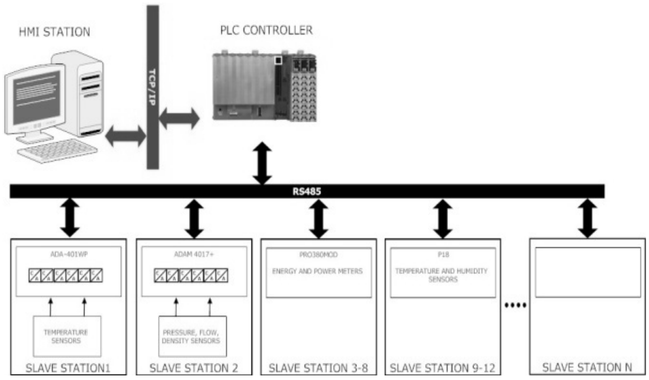


Fig. 2. Elements of the control system with monitoring functions

The PLC controller from the Bernecker&Rainer (CP1301) is the main element of the monitoring and control system. First of all, the PLC controller is a data collector from a plant i.e. the refrigeration unit using a serial infrastructure type RS485 and a Modbus RTU protocol. The PLC controller is a master in the serial network and measurement devices are slaves with specific ID numbers. This network may be rebuilt and additional devices may be introduced. Besides that, it is possible to build a wide distributed network up to 1200 m length. Based on preliminary assumptions the authors configured:

- One temperature measurement device using one wire technology (ADA-401 WP - one wire concentrator with 20 PT1000 sensors)
- One analog – digital device with eight channels to get data from pressure, density and flow sensors (Adam4017+ from Advantech)
- Six energy and power measurement devices (PRO380-Mod from Astat).
- Four temperature and humidity measurement devices (P18 from the Lumel)

For the fluent communication, all devices should be configured with the same network parameters: baudrate – 9600 kbps, parity – None, Bit stop – 8. It was impossible to speed up a serial network using a faster baudrate, because of technological limits of energy modules. A specific slave device has its own system of addressing, given as an example in Table 1, more or less based on the original Modbus RTU specification.

Tab.1. Addressing system of slave devices

Device	Address	Data type	Physical range/Unit
ADA-401WP	40001-40019	INT	–10 –60 / ºC
Adam 4017+	40001-40007		4–20 / mA
PRO380-Mod	408321 – 408324 412289 – 412289	UINT UINT	- / kW - / kWh
P18	47501 – 47503 47504 – 47505	UINT UINT	–20 –60 / ºC 0–100 / %

Both ID numbers and addresses are fundamental for a proper implementation of a Modbus master program and correct data transactions between it and slave stations.

Additionally, the PLC controller is a data source for the SCADA environment implemented in a selected computer (a HMI station) in the Ethernet network. It is possible to use two different technologies i.e. DDE (Dynamic Data Exchange) and/or OPC (Open Process Control). In the first case, a separate program named I/O driver should be executed and still working in a background of the SCADA system. In the configuration file, there should be written the definition data like: service name (PVIDDE), topic name (any string) and item name, which can be the same as the variable data used in the PLC controller program, shown in Figure 3. What is important is that any DDE type program (e.g. MS Excel, Matlab, Calc etc.) can exchange data with an I/O driver [3].

The DDE technology is simple in use, but its efficiency dramatically goes down with increasing number of variables. Besides that, an I/O driver working in the background should be still examined and re-executed when it is frozen.

```
  * time (ms) for refresh cycle
  I=250
  * DDE topic definition
  CPU:#Ina2000/PVITEST{},ERR="E#";
  *An item definition
  aiTemperaturaPV1:"CPU{/DAIP=82.145.73.193
/REPO=11159}/Main{Main}/Cooler[0].aiTemperaturaPV{Cooler[0].aiTemp
eraturaPV}", RF=1,DA=CPU;
```

Fig. 3. Exemplary DDE driver configuration

The authors decided to use the OPC technology in the final version of the system, because it is more reliable than the DDE solution [2].

A basic idea is similar to a DDE concept – both based on a server – client technology, but a configuration of the OPC server and tagnames related to it is different.

In the case of a CP1301 device, an OPC server may be run as an internal service of the controller. It means that its efficiency does not depend on any OS system used in a HMI station. A proper preparation of the OPC server consists of two stages: an OPC tagnames definition and mapping them on the server.

Tagnames may be declared using an XML structured file, which is shown in Figure 4.

```
<?xml version="1.0" encoding="utf-8"?>
<Tags>
  <Tag
        Type="BOOLEAN"
        Name="Cooler[0].uiValve[0]"
        Description="Zawór1"
        SourceVariable="Cooler[0].uiValve[0]"
        SourceProgram="Software.Main"
        SourceDatatype="BOOL"
        SourceDerivationBaseDatatype="BOOL">
        <Format
                  IsVector="False"
                  IsArrayElement="False"
                  Index="0"
        />
        <Access IsProtected="False" Read="True" Write="True" />
        <Values Manual="False" ManualValue="" />
  </Tag>
</Tags>
```

Fig. 4. Exemplary OPC tagname declaration

Finally, all the declared tagnames should be placed on the OPC server, which is known as a mapping process. As a result, a mapping configuration file is created with a structure shown in Figure 5.

```
<?xml version="1.0" encoding="utf-8"?>
<Map>
    <Tag Name="Cooler[0].uiValve[0]" Scope="OPCConfig">
        <PV Name="Cooler[0].uiValve[0]"
                Task="Main"
                    DataType="boolean"
                IsVector="False"
        BitNumber="none" />
  </Tag>
</Map>
```

Fig. 5. Exemplary OPC mapping configuration

Now the PLC controller is an OPC server and it is possible to exchange all declared tagnames using any SCADA system (e.g. iFix, InTouch, Trace etc.) under control of OPC drivers related to it.

Based on the OPC data an HMI station was built. The HMI station has several functions, but three of them are the most important: visualization of the refrigeration unit, opportunity of control it automatically and manually and data acquisition.

Besides being the data source and data collector, the PLC controller enables implementation of various temperature control algorithms to make it stable. In this stage of development, the authors prepared two operation modes: manual and automatic based on the two-state algorithm. Besides temperature stabilization, the control system should activate all actuators of the unit (valves, fans, heaters, compressor) in the specific order according to the selected operation mode.

The refrigeration unit operates in the following three modes:

- the device is not ready - the system is not switched on - should be supported software module Switching System;
- the device in the A mode - supported A module;
- the device in the B mode - supported B module.

The software module Program Organization included in the main program is responsible for proper organization and correct functioning of the entire program. Switching A or B should be precede by pre-set of the expected temperature. Moreover, the system must be switched on. During A and B modes there are executed sub-programs responsible for the temperature stabilization and the security control.

The architecture of the control system is shown in Figure 6.

The operator of the refrigeration unit can switch on the unit in two ways: from the HMI station, which is a default option and from the internal webserwer, which is generally recommended for the service team.

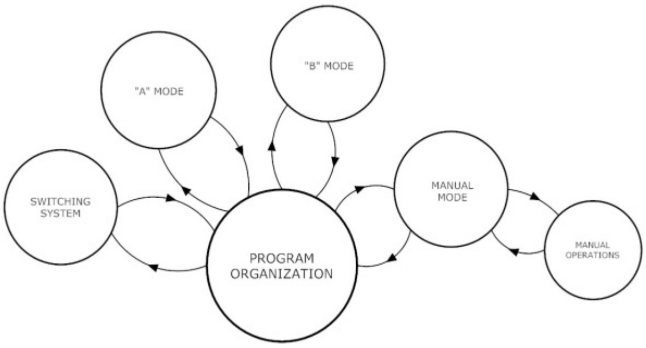


Fig. 6. Structure of the refrigeration unit control system

4. Experiments

The developed system was experimentally examined by the two-state temperature control algorithm implemented for stabilizing the temperature inside the cooling chamber and the control algorithm for the switching of operation mode between A and B.

The recorded measurements enable displaying the dynamic changes in the system parameters. The selected results of real time experiments are presented in Figures 7 and 8.

Figure 7 shows the pressure change in the evaporator and subcooler, and the effect of the two-state control of temperature. The average temperature in the chamber oscillates symmetrically around the set value of −10°C.

The points of switching the operation mode from A to B and vice versa in which there is a slight disturbance of the temperature in the chamber due to the thermal inertia of the system, are also shown. The assumed temperature control algorithm is realized until the next switching operation.

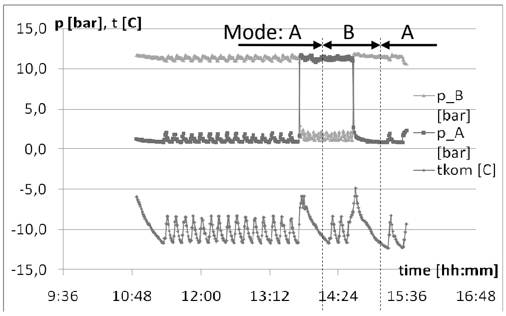


Fig. 7. Pressure change in the heat exchangers (p_A, p_B) and average temperature in the cooling chamber (tkom)

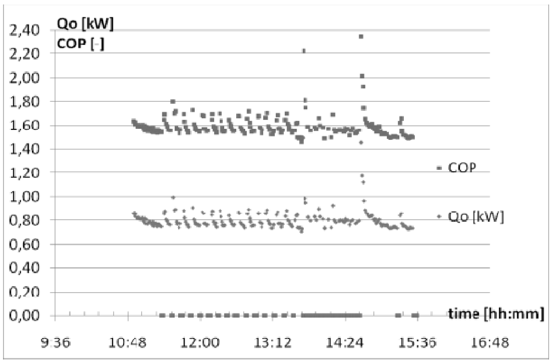


Fig. 8. Cooling capacity and energy efficiency of the refrigeration unit

Figure 8 shows the change of the cooling capacity and energy efficiency of the refrigeration unit. The monitored parameters increase periodically at the time of mode switching, due to additional subcooling of the liquid refrigerant resulting from the implemented recovery of cold. This effect depends on the amount of cold accumulated in the frosted heat exchanger and will be the subject of further studies.

5. Conclusions

At this stage of the project, both implemented control algorithms provided the sufficient quality of the temperature and operation control. The recorded measurements enable displaying the dynamic changes in the system parameters and calculations of the cooling capacity and the COP.

The results of real time experiments confirm the correctness of implemented solutions for energy efficiency monitoring of the refrigeration unit.

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