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Implementation of heat exchanger performance testing system of heat transfer and flow resistance

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Abstract: A heat transfer performance testing system is presented with its hardware structure, operation principle, and software control and measurement system. Working fluids of the subsystem include thermal conducting oil, compressed air, glycol water solution and water as the heating fluids, and air and water as the cooling fluids. The heat transfer performance testing of heat exchangers can be conducted not only for a conventional one heating fluid to one cooling fluid, but also for a compound air cooling heat exchanger with two or three heating fluids in parallel or in series. The control and measurement system is implemented based on a LabVIEW software platform, consisting of the data acquisition and process system, and the automotive operation and control system. By using advanced measuring instruments combined with sound computer software control, the testing system has characteristics of a compact structure, high accuracy, a wide range of testing scope and a friendly operation interface. The uncertainty of the total heat transfer coefficient K is less than 5%. The testing system provides a reliable performance testing platform for designing and developing new heat exchangers.

Key words: heat exchanger; heat transfer performance; testing system; LabVIEW

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The heat exchanger is widely used in engineering and industries. Various kinds of heat exchangers with different structures meet the needs of different processes. With the development of heat transfer enhancement technology, the trend of the heat exchangers is towards small size and light weight. The plate-fin heat exchanger is considered to be one of the most promising kinds of heat exchangers due to its high efficiency and compact structure[1-5]. Improving the performance of the heat exchanger as one of the most widely used pieces of equipment of the energy system is significant in increasing system energy utilization efficiency and reducing energy consumption. Therefore, using the appropriate methods to test the performance of the heat exchanger is particularly important[6-7]. Heat transfer capacity and flow resistance are two main performance indices for evaluating a heat exchanger. A heat exchanger performance test is to simulate the operation conditions of both the side temperature and the flow rate and to measure and compare the heat transfer capacity and the flow resistance with the design requirements under these conditions.

LabVIEW developed by American National Instrument Company is a program environment with a graphical programming language in the form of a block diagram[8]. With the LabVIEW program it is easy to integrate different data acquisition hardware and to communicate with several different industrial bus-bars in a variety of fields. LabVIEW provides the best development platform for advanced testing instrument software, and it has become the industrial standard of a graphical programming language, which has been widely accepted as a standard data acquisition and control software by industries, academic circles and research laboratories [7-10].

1 Structure of Test Rig System

The performance test rig is designed and installed to simulate the working conditions within the design parameter scope of the testing heat exchangers, and then to verify the design parameters and operational performances of both the heat transfer and the resistance, thus providing reliable measurement data for selection, design and verification of the heat exchangers. The use of heat exchangers involves two or more fluids. This recently-built system can simultaneously test performances of the heat transfer and the flow resistance of a compound heat exchanger with up to three heating fluids. Therefore, it broadens the test scope and meets the industrial needs in practice.

The testing system includes five sub-systems. They are the cooling air system, the oil system, the compressed air system, and two water systems namely the Y system and the S system. The medium of the oil system is thermal conducting oil, while the media of the Y system are either glycol-water solution or water, and the medium of the S system is water. The S system has two functions for either heating water or cooling water circulation.

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1.1 Cooling air system

The cooling air system provides the main cooling fluid to test the heat transfer performance. The layout of the cooling air system equipment is shown in Fig. 1. In addition to providing the air flow within the design range and measuring the air flow rate, the temperature at the inlet and the outlet of the testing heat exchanger and the differential pressure, the cooling air system can also regulate the inlet air temperature from ambient temperature to 60 ℃ by circulating part of the warm air mixing with the fresh cold air.

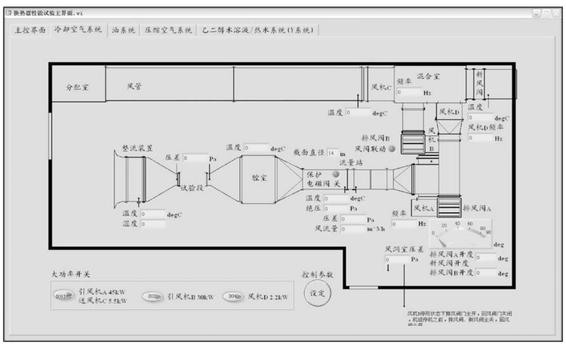


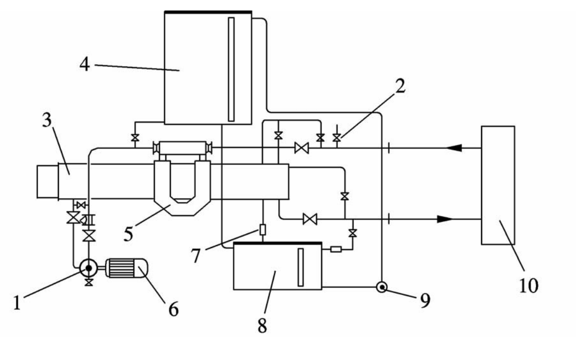
Fig. 1 Interface of cooling air system

The cooling air in the wind tunnel room flows through a rectifier to the testing heat exchanger section for uniformity distribution and the average inlet temperature is measured by a rake-shaped air sampling device. The testing heat exchanger is mounted on the inlet of the wind tunnel chamber. In the testing section, the cooling air exchanges heat with the heating fluids flowing through the inner channels of the heat exchanger. After warming up, the air is induced into the insulated wind tunnel chamber driven by fan A alone or with fan B in parallel, where the warm air goes through another rectifying device for uniformity before measuring the average outlet temperature of the heat exchanger with another rake-shaped air sampling device. Then the air goes into one of the three airflow measurement stations for measuring the airflow rate. Then the air is introduced into a three-way chamber, of which the two outlets connect to the suctions of fan A and fan B, respectively. Each fan boosts air into a T-duct and then the air splits into two parts. One part is blown out of the room through an exhaust damper, the other goes into the mixing chamber and mixes with the fresh air from the outside.

The flow of fresh air to the mixing chamber is controlled by a fresh air damper. The mixed air is then sent into the air duct by fan C, and then discharged to the room through a porous plate of the distribution chamber. The flows of return air, exhaust air and fresh air are controlled by adjusting the corresponding air damper to fit the inlet air temperature requirement. The adjustment of the return air damper, the fresh air damper and the exhaust damper of fan A is implemented with a single inlet air temperature adjustment command. The fresh air damper and the exhaust damper of fan A are in the same direction, while the return air damper of fan A is in the opposite direction. The larger the exhaust and fresh air dampers open, the smaller the return air damper opens, and then the temperature decreases. The dampers of fan B follow the damper adjustment command only in the case that fan B is in operation; otherwise, both the return air damper and the exhaust damper of fan B are closed. All of the exhaust and fresh air dampers are closed when they are out of service. Also there is a manual isolation damper at the entrance of fan B.

1.2 Oil circulation system

The oil circulation system is a closed loop including an oil pump, an electric heater, mass flow meters, an oil tank and connecting pipes as shown in Fig. 2. The pump flow rate is controlled by the frequency inverter. The maximum flow rate of the system can reach 600 m^3/min.



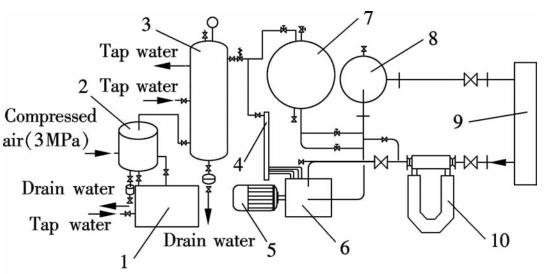
1—Pump; 2—Valve; 3—Heater; 4—Upper tank; 5—Flow meter; 6—Motor; 7—Transparent tube; 8—Lower tank; 9—Small oil pump; 10—Testing heat exchanger

Fig. 2 Schematic diagram of oil system

Next to the exit of the oil pump is an electric heater, and its total heating power is up to 234 kW, which is divided into three groups. Each group is controlled by the AC contact relay and the heating power is adjusted by a set of solid state relays. An ELITE-CMF200 type mass flow meter (precision 0.05%) produced by MicroMotion is installed in the return oil pipe line to measure both the mass and the volume flow rates. The inlet and outlet of the testing heat exchanger are connected to the oil system by corrugated connection pipes. An upper tank is installed above the oil circulation loop to provide a positive suction head for the oil pump and also to compensate the volume expansion or contraction due to temperature variations. A lower tank is set up for accumulating the oil drained from the testing heat exchanger and for filling as well. To facilitate draining the oil from the testing heat exchanger, a low pressure compressed air line is connected to the system through the valve at the upper right corner as shown in Fig. 2.

1.3 Compressed air circulation system

The schematic diagram of the compressed air system is shown in Fig. 3. The main loop is composed of a circulation compressor, an electric heater, and a mass flow meter, and it is connected with both the inlet and the outlet of the testing heat exchanger. The mass flow meter is of the same model as the oil system, with a precision of 0.35% for gas flow measurement. The flow rate is controlled by the frequency regulation of the compressor and the maximum flow rate of the system can reach 46 m^3/min in normal air. The compressor is equipped with a set of mechanical seals, to which a small quantity of sealing air is supplied. The system is also connected with a tank of 0.7 m^3 volume to regulate and stabilize the system pressure. The tank and the main loop are connected by a pair of solenoid valves which are automatically open in both directions while the compressor is on. The supply of compressed air is from an air source of 3 MPa. Because of high moisture in the air source, it will bring big errors in the heat balance of the performance test. The compressed air system adopts a spiral plate heat exchanger as a dehumidifier, and the moisture is removed under the high pressure condition. The air flows to a storage tank and then flows through a pressure reduction valve to insure the appropriate air pressure for the stabilized tank and for the mechanical seal of the compressor. The pressure of the compressed air system can be regulated by adjusting the pin-valves of the mechanical seal supply to compensate for the leakage, or by switching on either the supply or the vent solenoid valves during start-up.



1—Water chiller; 2—Spiral plate heat exchanger
3—Gas storage tank; 4—Mechanical seal gas supplier
5—Motor; 6—Circulation compressor; 7—Gas tank
8—Heater; 9—Testing heat exchanger; 10—Flow meter

Fig. 3 Diagram of the compressed air system

1.4 Water circulation system

The water circulation system consists of a Y system and an S system, which are arranged on a single bench as shown in Fig. 4. The Y system uses glycol solution or water as heat working fluids, and the circulation loop is similar to that of the oil system. The S system can be used as either a heating water or a cooling water circulation system. When it is used as a heating water circulation system, the electric heater of the Y system should be used. The advantage of using the S system pump for heating water circulation is that the glycol solution in the Y system pump and the relative pipes need not be evacuated. When the S system is used as the cooling water circulation system, it either connects to the cooling water supply from the cooling tower of the factory, or adopts another plate-fin heat exchanger cooled by the wind tunnel at the outlet of the testing heat exchanger to form a closed circuit, the cooling water temperature is adjusted by regulating the fan motor frequency. The two water systems are combined with the cooling air system, and the heat transfer performance of the heat exchangers can be tested by heating and cooling medium pairs including water-water, glycol solution-water, water-air, and glycol solution-air. The design of the Y/S system meets the requirements of a multi-function, compact structure, and it is cost saving.

Fig. 4 Photo of water system

2 Data Measurement and Acquisition

The main heat transfer performance parameters to be measured include the fluid temperatures and differential pressures at the inlet and the outlet of both sides of the testing heat exchanger and the flow rates of both sides. For the compressed air system, the pressure at the inlet of the testing heat exchanger is also included. The inlet temperature of cooling air is measured in the rectifier. A rake-shaped sampling pipe is set at the middle of the rectifier. The mixed air is extracted by a sampling fan. The temperature and humidity of cooling air at the inlet of the testing heat exchanger is then measured in the intake tube placed in front of the sampling fan by a sensor produced by Vaisala. The temperature of warm cooling air at the outlet of the testing heat exchanger is extracted by the sampling fan through a rake-shaped sampling device in the insulated chamber of the wind tunnel and measured by a Pt100 thermometer (±0.15°C precision). The air flow rate through the testing heat exchanger is measured in one of the three airflow measurement stations. The airflow measurement stations are of different ranges, the diameters of which are 28″, 14″ and 8″, respectively. The airflow covers a range of from 600 to 50 000 m^3/h. A super differential pressure transmitter (0.025% precision) is used for the airflow measurement stations, and others use classical differential pressure transmitters (0.055% precision). The air flow rate is calculated by a computer program according to the selected diameter of the airflow measurement station, the temperature, the pressure and the differential pressure at the air flow station for velocity and density. The temperatures of other systems are also measured by Pt100 thermometers and the flow rates are measured by MicroMotion mass flow meters. The selection of a high precision measuring instrument can greatly improve data precision and, thus, reduce uncertainty of the experimental results.

Data measured by the thermometer and the differential pressure transmitter are obtained by an Agilent 34970 data acquisition unit. Through the serial ports, the computer connects with a data acquisition unit and receives data. The computer sends a data acquisition command every 15 s. The data acquisition instrument scans data after receiving the command and delivers them to the computer for processing and then displays the target parameters on the screen. The mass flow meter and the motor frequency inverter communicate with the computer through a bus 485 and serial ports. The computer also routinely collects data measured by the flow meters. The operation frequency can be set up and adjusted by the computer.

3 Control and Implementation Program

The performance test rig system has multiple subsystems and various precise measuring instruments. It is necessary to collect and process a large amount of data. This test system program uses LabVIEW as a software platform to control the system. The program starts with selecting the heating and cooling systems for actuation, and then selects the airflow measurement station identical to the actually used one. If the Y system is selected, there is also an interface dialog for selecting the concentration of the glycol solution. The main interface with the selected subsystems is shown in Fig. 5.

The main interface provides a main switch button, a data acquisition button, a heat transfer calculation button and an exit button for controlling the overall testing system. And it is also used for displaying the whole parameters of the subsystems. The first step is to click the main switch button to start the experiment. The main switch button is also used as a software protection button in case of emergency. After finishing the preparation, click the data acquisition button in the main controlling interface, and open two files for data saving. The computer will send

Fig. 5 Main interface of control and measuring parameters

monitoring and data acquisition commands. Then the data acquisition unit sends the data back to the computer and the data will be processed, displayed and saved in the computer. The computer executes a scanning every 15 s and the average value of four scannings per minute is recorded. In the main control interface there are also several buttons for displaying two curves of each involved system of the flow rate and inlet temperature, which makes it easy for the operator to monitor the stability of the parameters.

The performance test system includes five subsystems. The structure of the control interface of each subsystem is similar. The switch buttons of each subsystem are mainly used to start or stop the power equipment (pumps, fans, compressors, etc.) and the heaters. The parameters of the current system are also displayed at the corresponding position of the system schematic diagram. The heater switch buttons interlock with the power switch for safety by software. For heating systems, only when the pump or the compressor starts working, the relay of the heater can be on so as to avoid overheating or burning caused by wrong operation.

The flow rate and the inlet temperature of the testing heat exchanger can be adjusted by clicking the control parameter setting button and then the control parameters dialog window is open. Either the manual or the automatic button is selected to regulate the control parameters. When applying manual adjustment, the control value such as frequency or percentage of heating should be input in the corresponding block. While if applying automatic adjustment, the target value of the control parameters, namely the flow rate or temperature, should be input in the corresponding block. The computer controlling system will calculate the value of the control parameter according to the current state and automatically adjust the frequency or percentage of heating until the control parameter approaches the target value.

When the parameters tend to be stable, click the heat transfer calculation button in the main interface, and then a dialog window is open. The main heat transfer parameters including the heat transfer quantity of the involved system and the relative deviation of heat balance are displayed.

The operator can click either the save-to-file button or the quit button to save or quit the present displayed data.

A heat transfer performance test on a water to water tri-section helical baffle heat exchanger [11] with a tilt angle of 32° was performed on this test rig. The heating water goes along the tube side and maintains unchanged parameters, while the cooling water takes a shell side helical channel and changes the flow rate step by step. Fig. 6 shows the curves of temperatures at the inlet and the outlet, mass flow rates and pressure drops of both heating water and cooling water from the recorded experimental data of the whole process. It can be seen that the equilibrium of the heat transfer parameters is very fast. Fig. 7 shows the curves of the overall heat transfer coefficient K and the transferring heat of both the heating water and the cooling water from the selected heat transfer equilibrium data of the performance test. The maximum deviation of the transferring heat of the two sides is less than 2%. From the uncertainty analysis, it shows that the uncertainties of the overall heat transfer coefficient K and the pressure drop Δp are less than 5% and 0.5%, respectively for normal testing parameters on this test rig.

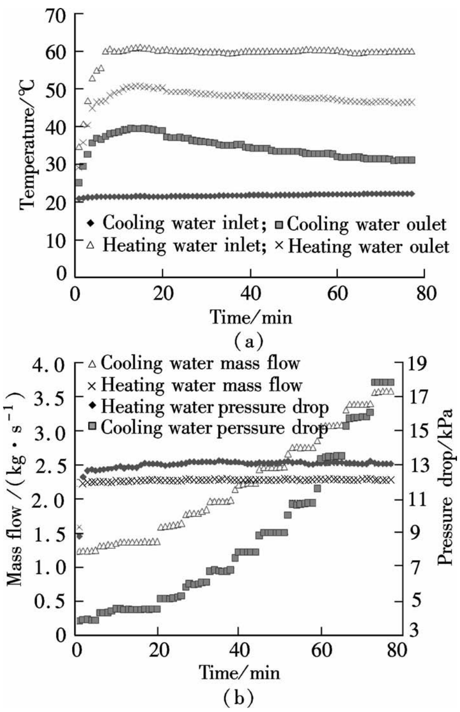


Fig. 6 Recorded experimental results of a heat exchanger. (a) Temperature; (b) Mass flow and pressure drop

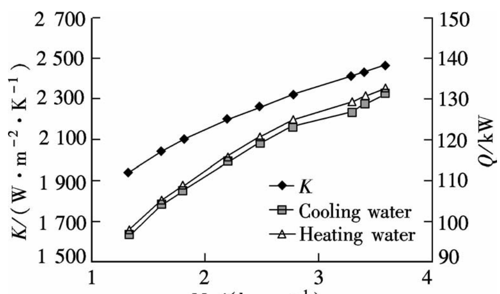


Fig. 7 Overall heat transfer coefficient and exchange heat vs. mass flow of cooling water

4 Conclusion

Five different fluids are used as the working circulation fluids in the heat transfer performance test system. This test system can simultaneously conduct performance tests of the heat transfer and flow resistance of a compound heat exchanger with up to three heating fluids. The testing and controlling program is based on LabVIEW, which can make full use of the excellent software function to achieve a centralized controlling function. Data acquisition and record saving are realized automatically, which can facilitate the testing work efficiency. High-precision measuring instruments are used to improve the accuracy of collecting parameter data of both cooling and heating fluids, which can reduce the test uncertainty.

This testing system is well designed for plate-fin heat exchangers as well as for other kinds of heat exchangers, and it is very fast in achieving the stability of heat balance. The results of many performance tests show that most of the relative deviation of heat transfer quantity of both sides varies within −3% to +5%. This test rig system can provide reliable test parameters for heat exchanger design and development.

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换热器传热与流动阻力性能试验台系统搭建

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摘要:介绍了换热器传热性能试验台系统的硬件构成、运行原理、软件控制和测量系统. 试验台系统由导热油、压缩空气、乙二醇溶液和水 4 种不同热流体与冷风和冷却水 2 种冷流体为循环工质的子系统构成,不仅能进行上述热流体对冷风或冷却水的一对一试验,还可以进行并联或串联的 2 种或 3 种热流体对冷风的复合型换热器的传热性能测试. 控制和测量系统以 LabVIEW 软件为平台,包括试验数据采集和处理系统以及自动运行与控制系统,借助完善的软件控制与先进测量仪器的相结合,使系统具有结构紧凑,测量精度高,测试范围广,程序界面友好等特点,对于换热器总体传热系数 K 的不确定度小于 5% ,为新型换热器的设计和开发提供了可靠的测试平台.

关键词:换热器;传热性能;试验系统;LabVIEW

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