Design and Implementation of Measurement Setup for AIRCOOLER I prototype testing

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Abstrakt
Cílem této práce bylo postavit pokusnou měřící trať pro testování prototypu chladícího zařízení nazvaného AIRCOOLER I. Zařízení AIRCOOLER I produkuje pomocí vírových trubic velmi studený vzduch použitelný pro chlazení. Pro měřící trať byly vybrány vhodné senzory teploty, tlaku a průtoku vzduchu. Byl zapojen přívod stlačeného vzduchu a vstup i výstupy prototypu byly osazeny senzory pro sledování jeho funkce. Pro určení chladicího výkonu zařízení byl sestaven elektricky vyhřívaný výměník, který je chlazen vzduchem z proměřovaného prototypu. Pro zobrazení a archivaci dat je užit automatizovaný systém sběru dat založený na software PVSS II. Na měřící trati bylo provedeno několik ověřovacích měření správné funkce tratě. Funkce a chladící výkon prototypu AIRCOOLER I jsou v souladu s předpoklady, nejnižší dosažená teplota vzduchu na výstupu ze zařízení byla méně jak -50 °C.

Klíčová slova
Automatizované měření a sběr dat, měření teploty a průtoku vzduchu, chlazení, vírové trubice, stlačený vzduch

Abstract
The testing setup for cooling device prototype named as AIRCOOLER I was built. AIRCOOLER I device produces very cold air using vortex tubes. Suitable sensors for temperature and pressure and air flow measurements were selected. Compressed air tubing, sensors and power sources were installed and connected to AIRCOOLER I prototype. A heat exchanger to be cooled by device was built and it will serve to evaluate cooling capacity of device. Electrical heaters were installed on heat exchanger. The DAQ system based on PVSS II is used for sensor values display and data archiving. Several verification runs were performed with realized setup. The cooling performance of AIRCOOLER I seems to be in accordance with expected values and minimal temperature up to -50°C has been reached at the outlet of AIRCOOLER I.

Keywords
Automated measurement and data storage, measurement of temperature and airflow, refrigeration, vortex tube, compressed air

1. Introduction

The aim of this work is to prepare a setup for tests of cooling performance of the prototype device called "AIRCOOLER I". The device has been developed at the Department of Applied Physics and manufactured by the DUO-CZ, s.r.o. in Opočno. Several tests were performed to verify the installation and basic functionality after the AIRCOOLER I test setup had been built. The prototype of the cooling device can produce a stream of cold air at temperature of - 50 °C. Such cold air can be further used for cooling of various heat exchangers or it can be directly aimed at the objects to be cooled. The AIRCOOLER I device requires supply of dry air at the room temperature with the inlet pressure between 7 and 9 bars. This compressed air is only energy source needed for the AIRCOOLER I operation, in other words no electricity is required to power the device. A portion of supplied air is cooled down and leaves the device as produced cooling medium for further use. Remaining flow is divided to three different outputs and wasted since the temperatures of these output streams are higher than that of the produced cooling air. A relatively small dimensions and low weigh of the device provide flexible and mobile cooling solution for various applications.

1.1 Vortex tubes

There are two counter-flow vortex tubes installed in the AIRCOOLER I. The vortex tube, also known as the Ranque-Hilsch vortex tube, is a simple energy separating device consisting of tube of special shape which divides input compressed air in two streams, a cold one and hot one [4], [8]. The tube does not need any other source of energy except for the compressed air. What is more, it does not contain any moving parts, so there is very small risk of failure. It is a compact device, easy to produce, install and operate.

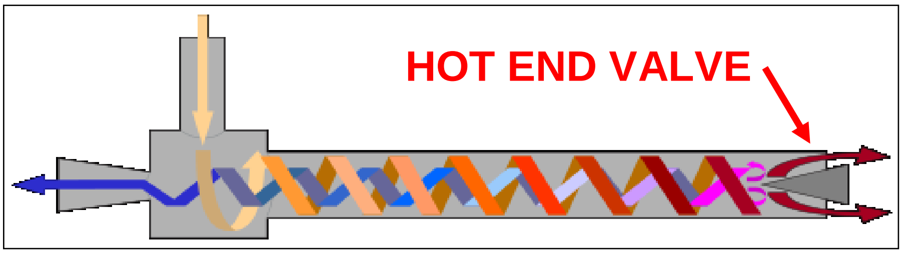

Figure 1: *Schematic diagram of counter-flow vortex tube.*

The vortex tube has two outputs – hot and cold – located on each end of the tube. The input is perpendicular to the tube axis. There is a setting screw on the hot end of the vortex tube allowing to adjust the ratio of the separated cold air to the hot air mass flows. The temperature of the cold air output is different for different adjustment of the mass flow ratio [3]. This is essential for the proper adjusting of AIRCOOLER I. It is usually necessary to find an ideal setting for specific application. One must consider whether the aim is to achieve as low temperature as possible but at small mass flow or to find a balance between sufficient mass flow and somewhat higher temperature.

1.2 Cooling device AIRCOOLER I

The AIRCOOLER is a compact box and its dimensions are 31 cm (width) x 20 cm (depth) x 36.5 cm (height). Weight of the device is 16.5 kg. There are five air pipe connectors on the box, four outputs and one input. The input is for compressed air and one of the outputs is cold cooling air outlet, remaining three outputs are for waste air of various (but relatively higher) temperatures.

There are two vortex tubes and one air to air heat exchanger in the box. The vortex tubes are connected in series: The cold air from the one vortex tube (also called secondary one) is used to precool the air for the main (primary) vortex tube in the heat exchanger. For the schema of all internal connections in the device see Figure 4.

The pressure of the input air needs to be at least 6 bars for an effective operation of the vortex tube. The output air pressure is nearly atmospheric. Because of this, the direct connection of the precooling tube output to the primary vortex tube input is impossible. Hence the input air of the primary vortex tube is precooled in the previously mentioned air to air heat exchanger.

Table 1: Summary of AIRCOOLER I connections.

No.	Connector usage
1	Compressed air input
2	Cooling air output
3	Heat exchanger waste air
4	Precooling VT hot waste air
5	Primary VT hot waste air

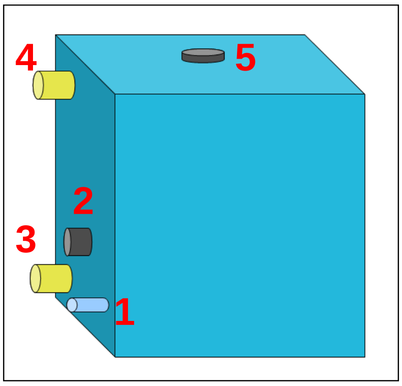

***Figure 2:** Positions of connections on AIRCOOLER I.*

The installed vortex tubes are manufactured by the ITW Air Management (USA) under Vortec brand. The manufacturer offers various sizes of tubes and some cooling solutions based on vortex tube principles. Two types of Vortec 106BSP-2-H and Vortec 106BSP-4-H are installed in our prototype.

Table 2: Overview of vortex tubes built in AIRCOOLER I.

Vortex tubes in AIRCOOLER I	
Maximal input air pressure	10.3 bar
Air input size	1/8" NPT (M)
Maximal pressure on output (backpressure)	0.4 bar
Vortec 106BSP-2-H	
Nominal air consumption for 6.9 bar input	57 Nl/min
Vortec 106BSP-8-H	
Nominal air consumption for 6.9 bar input	227 Nl/min

2. Setup building

Setup for the measurement has been installed in the laboratory of the Department of Fluid Mechanic and Thermodynamics of Czech Technical University in Prague where a sufficient source of compressed air is available. The hose of 10 mm inner diameter is used to supply the air from the mains. A pressure regulator is used to keep the inlet pressure for AIRCOOLER I stable. The Swagelok fittings are used to connect the plastic pipes that are used for input and output air.

It was decided to measure the temperatures of the input and all the output air streams in order to be able to monitor the operation of the device. The input air pressure is also measured, because the vortex tubes are very sensitive to its changes [3]. The volumetric flows of the produced cooling air and of the input compressed air were found to be essential for AIRCOOLER I performance evaluation.

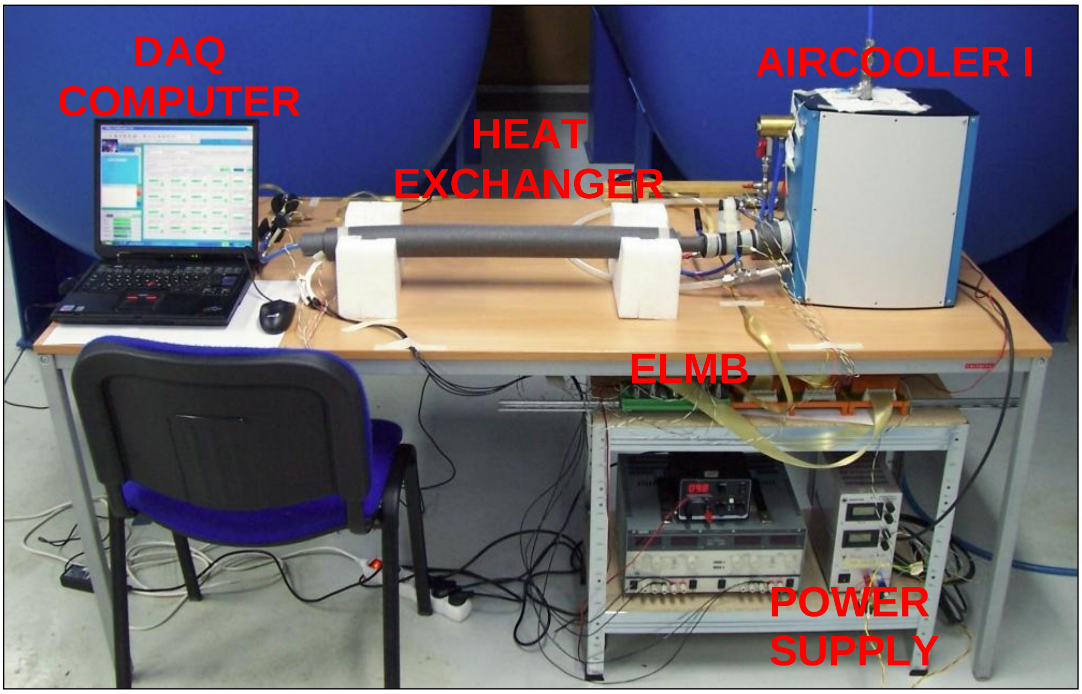

Figure 3: *Setup placed in the laboratory of Department of Fluid Mechanics and Thermodynamics. AIRCOOLER I is on the right hand side, heat exchanger is in the center.*

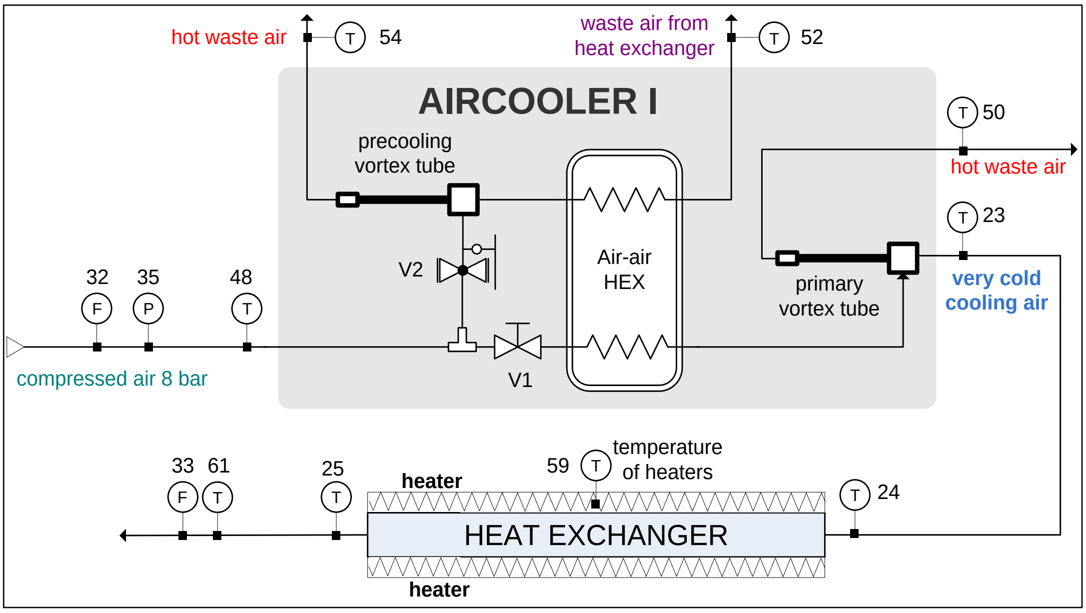

Figure 4: *The scheme of setup with positions of sensors and relevant sensor channel numbers.*

2.1 Heat exchanger

A heat exchanger with electric heaters was built in order to evaluate the cooling power of the prototype. This heat exchanger is cooled down by the produced cold air. There are temperature sensors installed at the inlet and outlet in two tailor-made plastic fittings It is easy to calculate the amount of transferred heat knowing the air mass flow and the temperature increase from input to output [1].

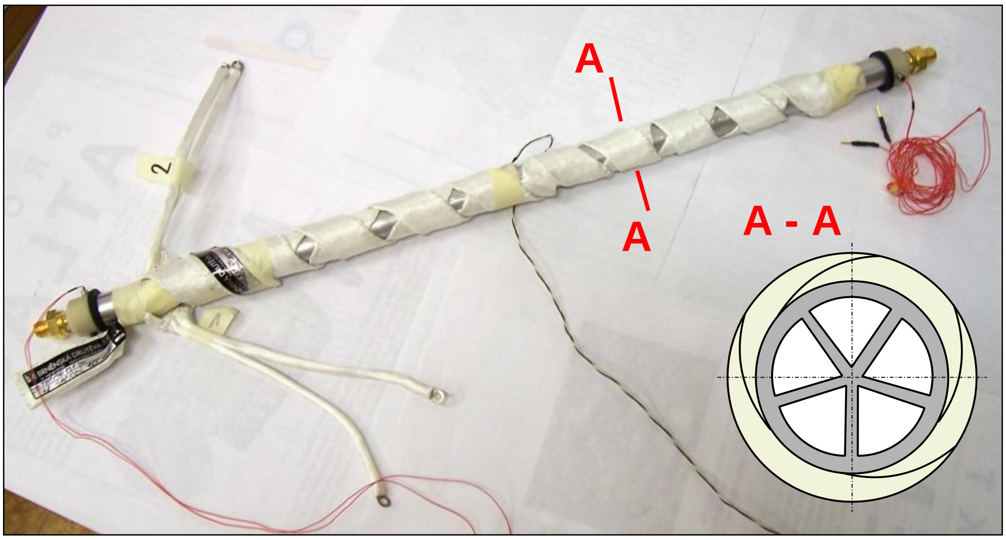

Figure 5: *Heat exchanger with two heating belts wrapped around the pipe outer surface.*

The heat exchanger is manufactured from a 600 mm long piece of aluminum pipe with inner diameter of 15 mm and outer diameter of 23 mm. There is a special insert with five fins put into the pipe (see detail in Figure 5). These ray-shape fins increase the heat transfer area 2.2 times when compared to the smooth tube. Two heating belts (type 231) made by Brněnská Drutěva are wrapped around external surface of the heat exchanger. The belts are made of braided fiberglass sleeve 1000 mm long and 30 mm wide and their nominal power is 155 W at nominal (maximal) voltage of 48 V. Heating belts combined with adjustable power supply offer a convenient way of evaluating of the AIRCOOLER I cooling performance. We can set supply voltage and calculate actual heating power of belts. This value should correspond with amount of transferred heat calculated from air mass flow and input-output air temperature difference.
The pipe with heating belts is well insulated by Armaflex insulation tube.

2.2 Temperature sensors

The NTC temperature sensors together with the Pt1000 are used to measure the temperatures. The NTC is the thermistor with non-linear temperature–resistance characteristic (with increasing temperature resistance decreases). A kapton coated NTC sensors are used, i.e. a whole sensor and wires are covered by kapton foil. Some Pt1000 sensors are used for the extremely low temperatures in the cold air lines. These sensors have linear characteristic.
Sensors were glued into short pieces of tube – see Fig. 6. These pieces can be mounted in the Swagelok "T" fittings so that the tip of the sensor is placed directly in the airflow.

Table 3: *Temperature sensors overview.*

signal name	channel	type
Cold VT	23	Pt1000
HEX IN	24	Pt1000
HEX OUT	25	Pt1000
air in VT	48	NTC
primary HOT	50	NTC
waste HEX	52	NTC
precooling HOT	54	NTC
bef. IST	61	NTC
heater	63	NTC

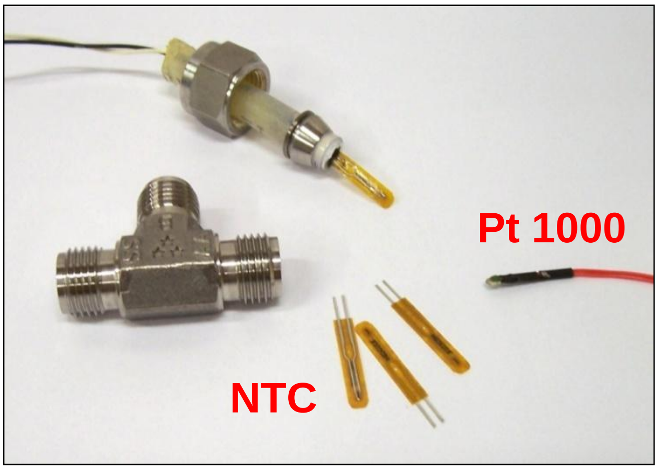

Figure 6: *Used temperature sensors, one prepared for assembly in fitting.*

2.3 Pressure sensor

The Huba Control 510 pressure voltage transducer is used for input pressure measurement. Measured pressure is recorded as a relative to atmospheric pressure (gauge pressure).

Table 4: *Pressure transducer properties*

Signal name	pressure IN
Signal channel no.	35
Pressure range	0-10 bar
Voltage output	0-10 V
Power supply	11,4-33 V

2.4 Flow sensors

Two different thermal mass flow meters are used to monitor airflows. The first one, Red-y Smart by Vögtlin Instruments AG, is installed in the main supply line. This sensor was delivered with a manufacturer calibration certificate. The Red-y sensor can provide either analog or digital signal proportional to the flow ranging from 6 to 300 Nl/min. The output digital signal is red by the supplied software via USB cable; this signal also includes the information about the airflow temperature.

Table 5: *Red-y flow meter properties.*

Signal name	flow IN
Signal channel no.	32
Serial No.	152233
Airflow range	6-300 Nl/min
Voltage output	0-10 V
Max air pressure	10 bar
Power supply	24 V

The second flow sensor is FS5 made by the IST AG (Innovative Sensor Technology). It measures the flow of cold air produced by the AIRCOOLER I. The sensor is installed at the heat exchanger output, where air is already slightly warmed up thus allowing the sensor to operate at moderate temperature. The sensor range is from 0 m/s to 100 m/s. The sensor isn't usually supplied "naked" so it needs to be mounted into some fitting or in a piece of tube. The internal diameter of the sensor mounting determines the range of measureable flow rates (with the increasing diameter the flow velocity decreases).

Table 6: *FS5 IST sensor properties.*

Signal name	flow COLD
Signal channel no.	35
Airflow range	0-150 Nl/min
Voltage output	0-2 V
Max air pressure	10 bar
Sensor flow speed range	0-100 m/s
Air temperature service range	-20 … 150 °C
Power supply	12 V

Our sensor was built into the 10 mm Swagelok “T” fitting. It was necessary to perform calibration prior to our measurements. The Ultrasonic Flow Sensor 1235-00-041 from Gill Instruments Ltd. was used as a reference flowmeter. The temperature of the air during the calibration was 16.5°C.

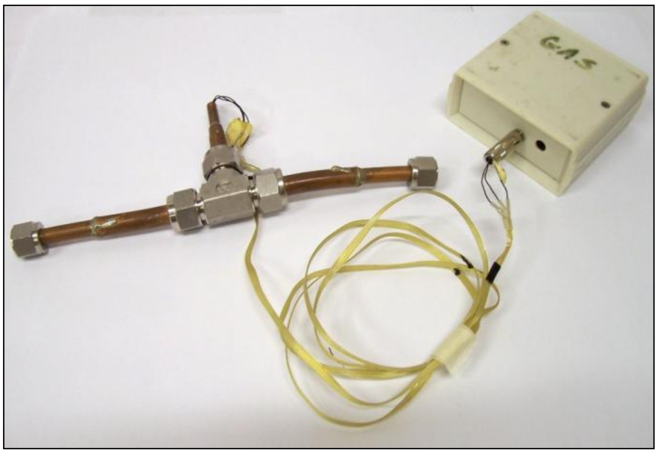

Figure 7: *The IST sensor built in 10 mm Swagelok “T” fitting with its readout box which powers the sensor and generates output voltage signal.*

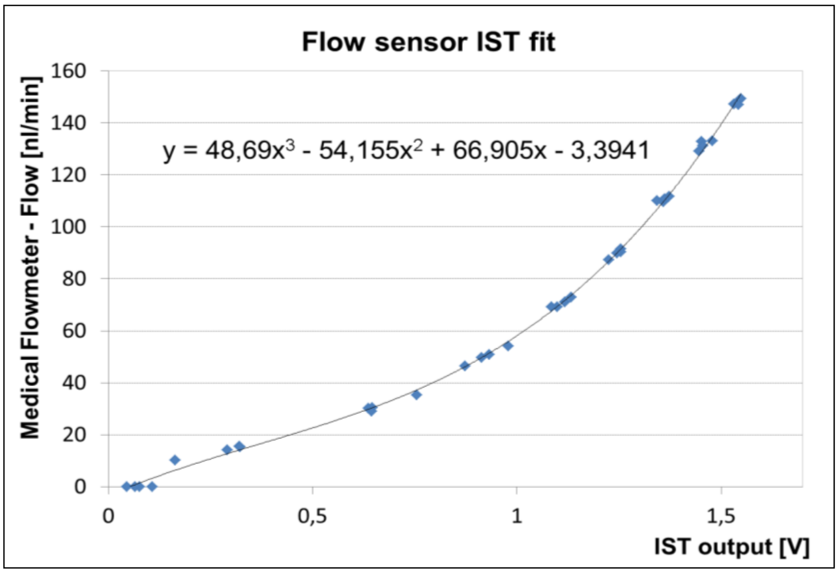

Figure 8: *The calibration of IST FS5 sensor.*

3. DAQ system

The Embedded Local Monitor Board (ELMB) is used for sensor analog signals readout. The ELMB128 is a universal plug-in I/O module for the process monitoring and control with analog and digital inputs and digital outputs. It can read values of up to 64 analog signals (channels 0 - 63) and send the measured values to the PC via CAN bus. There are variety of adaptors that enable to measure the resistance of two or four-wire Pt temperature sensors, NTC sensors and different voltage signals. All adapters are placed on the bottom of the board and they can be easily changed/replaced. A single adaptor serves usually for four channels.

We have used three different types of adaptors in total, two for the temperature sensors (NTC and Pt1000) and one for the voltage signals from flowmeters and pressure transducers (0-10 V).

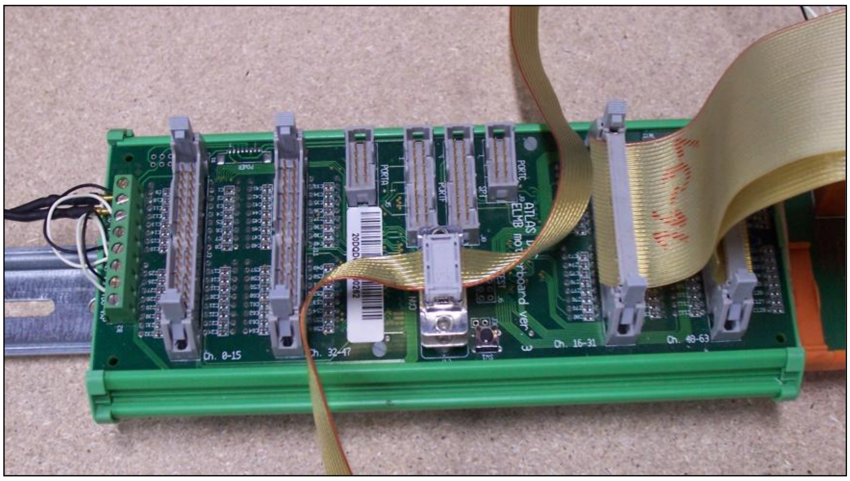

Figure 9: *The ELMB128 unit, cable in the middle is CAN bus, wide flat cables are used for analog signals.*

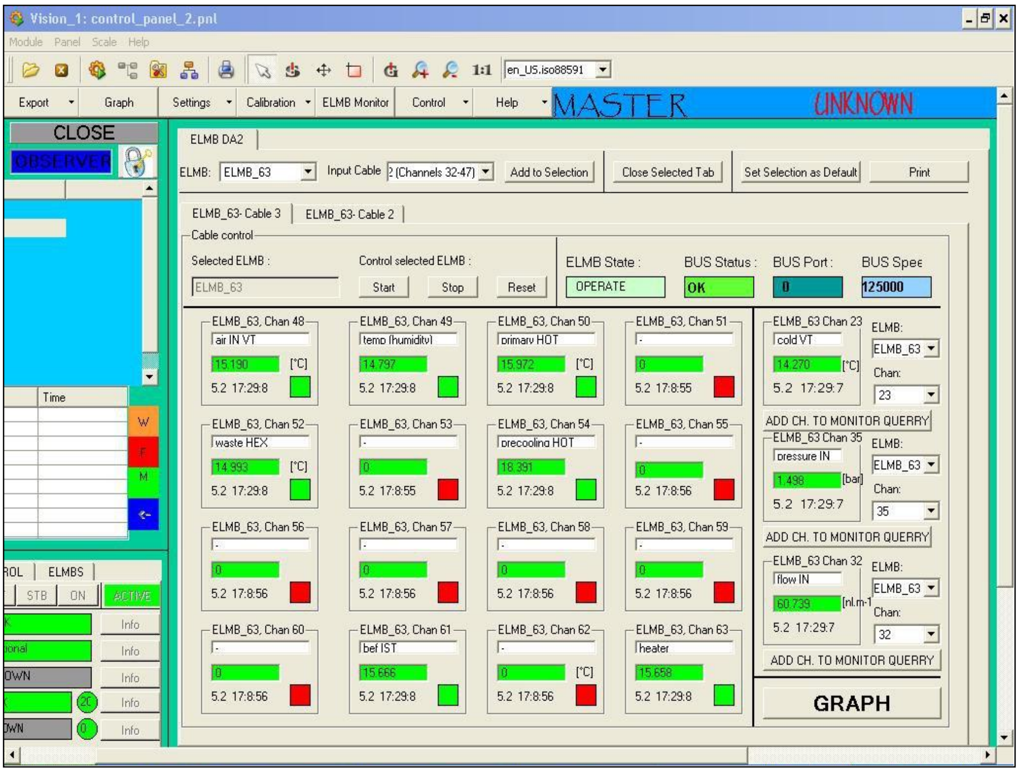

Figure 10: *Channel values visualization panel in PVSS II software.*

The ELMB unit is connected via CAN bus to a KVASER CAN/USB converter which is then connected to the PC. The data is read from ELMB via the CANOpen OPC Server. The PVSS II software is used for data display and archiving. It is a SCADA (Supervisory Control and Data Acquisition) environment containing a run-time database, an archiving, an alarm generation, a graphical editor, a scripting language and a graphical parameterization tool. PVSS II allows the user to design custom visualization panels and process control programs. Visualization environment previously developed by our group was used in this experiment.

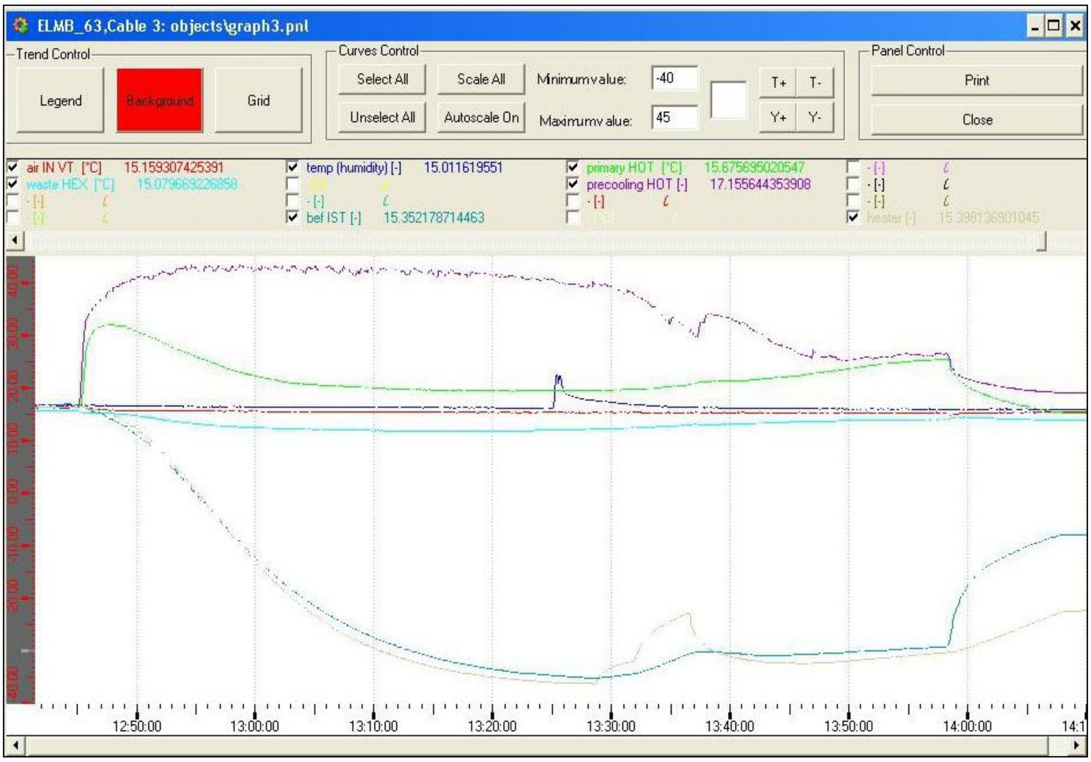

Figure 11: *Graph visualization of measured data in PVSS II.*

4. Measurements performed on setup

Several test runs were conducted to detect leaks and other hardware issues like malfunction or wrong position of components. The DAQ system and heating belts on heat exchanger were tested as well. The setup and the DAQ system worked well after some minor modifications and improvements. Measurements of basic operation parameters of AIRCOOLER I were carried out.

4.1 Compressed air consumption

Air consumption was measured to detect possible bottlenecks in prototype internal compressed air piping. Air consumption was measured for two different input air pressures: 6.9 bars (nominal pressure) and 8 bars (our testing pressure). Table 7 shows our measured values that are compared to the nominal values listed in the specifications of installed vortex tubes. The difference between the nominal and the measured air consumption of precooling vortex tube might indicate too small diameter of supply pipe inside the prototype. This phenomenon does not significantly affect the device performance (see further data).

Table 7: *AIRCOOLER I air consumption for different modes of operation.*

mode of AIRCOOLER I operation	measured air consumption (Nl/min)		nominal air consumption (acc. to VT specs.) (Nl/min)
	pressure 6.9 bar	pressure 8 bar	pressure 6.9 bar
only primary VT	55	57	57
only precooling VT	162	188	227
precooling and primary VT	215	260	284 (sum of above)

The AIRCOOLER I can produce about 30 Nl/min of cold air for input pressure of 8 bars and about 27 Nl/min for input pressure of 6.9 bars. These airflows represent approximately 12 % of the input compressed air. Have in mind that these figures are only indicative since the actual amount of produced cold air depends on the changeable setting of the hot end valve of vortex tube as discussed in the paragraph1.1,[3],[6].

4.2 Startup of the device

This test was conducted to find out two very important parameters: the lowest achievable temperature and time needed to achieve full cooling performance conditions.

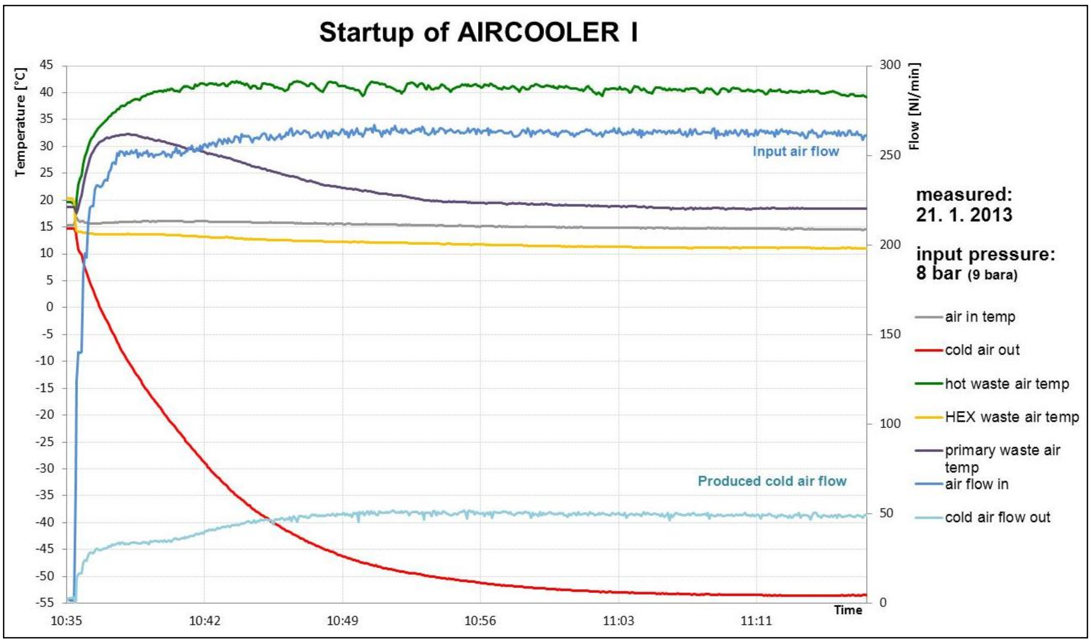

Figure 12: *Graph of startup test data. Cooling air temperature (red) exponentially decreases to -54 °C.*

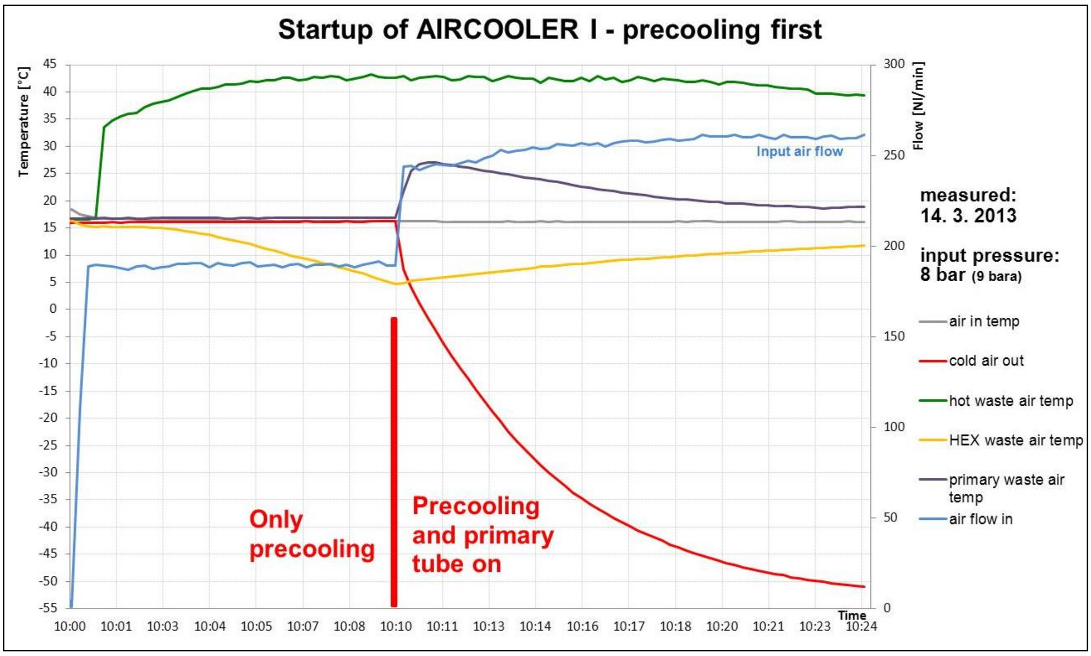

Figure 13: *Graph of gradual startup test data. First ten minutes did operate only precooling vortex tube. It took 23 minutes to reach -50 °C.*

It takes about 25 minutes to reach -50°C limit. The lowest observed temperature was -54 °C and it took 40 minutes of operation to reach it. We have tried to speed up this procedure through the following steps:

(a) using only the precooling vortex tube at the beginning of the test run

(b) turning on the primary vortex tube when the precooling heat exchanger is cooled down

However this procedure did not bring a significant improvement (see Figure 12).

5. Conclusion

The experimental setup was built for the AIRCOOLER I verification and its cooling power characteristics measurements. The setup was equipped with appropriate set of sensors monitoring the device performance. The heat exchanger with electrical heaters was commissioned and it can be used for testing of AIRCOOLER I cooling capacity. The setup, all the sensors and the data readout worked properly.

The prototype of the cooling device AIRCOOLER I can produce air as cold as -54 °C. The volumetric flow of the cold air is about 30 Nl/min and the start-up time of the device is 25 minutes. The device performance is in accordance with expectations based on our previous experiments with vortex tubes.

The setup will be used for further testing of the AIRCOOLER I. The measurements of the device performance with various settings of the vortex tube hot end valves and with lower driving pressures are expected soon.

All these measurements will be used as an input data for further studies and designing of the AIRCOOLER I control system. The ability to control the output temperature would greatly increase the possibilities of device application. We can foresee the Vortex tube applications in wastewater treatment unit being developed by the Department of Fluid Mechanics and Thermodynamics and in the applications of detector cooling at CERN where we have already tested some vortex tube cooling systems for AFP ATLAS project and SCT ATLAS project.

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