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Capabilities of a New Pressure Controller for Gas-Controlled Heat Pipes

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Abstract Pressure control is used in many metrological applications and for the control of thermodynamic quantities. At the Italian National Research Institute of Metrology (INRiM), a new pressure controller has been designed and assembled, operating in the pressure range between 4 kPa and 400 kPa. This innovative instrument uses a commercial pressure transducer with a sensitivity of 10^{-4} and several electro-valves interposed among calibrated volumes of different dimensions in order to realize known ratios for very fine pressure changes. The device is provided with several circuits to drive the electro-valve actions, for signal processing and transmission, and for both manual and automatic control. Input/output peripherals, such as a 4×20 dot matrix display and a 4×4 keyboard, allow setting of the parameters and data visualization, while a remote control port allows interfacing with a computer. The operating principle of this pressure controller has been recently applied, with excellent results, to control the pressure in gas-controlled heat pipes by using a standard platinum resistance thermometer as a temperature/pressure sensor, achieving in this case a relative sensitivity better than 10^{-6} in pressure. Several tests were also made to control the pressure by means of a commercial sensor. The device, its main components, and its capabilities are here reported, together with application tests and results.

Keywords Pressure control · Heat pipes · SPRT · Temperature

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1 Introduction

Research activities carried out in the Thermodynamics Division of the Italian National Research Institute of Metrology (INRiM) include the study of special devices for pressure control for temperature and pressure metrology. Previous methods were developed at INRiM and applied with satisfactory results for the pressure and temperature fine control of gas-controlled heat pipes (GCHPs) [1]. In recent years, an innovative pressure controller has been developed at INRiM, combining previous experience with new electronics, a new operating principle, smaller dimensions, and easy-to-use software. Thanks to the principle of using a standard platinum resistance thermometer (SPRT) inside a GCHP to replace the pressure sensors, as described in Sect. 3 of the present article, this innovative device has better capabilities than a high-quality commercial pressure controller. Commercially available pressure controllers hardly guarantee control at the level of parts in 10^{-6} over a comparable range, while the controller presented here is one order of magnitude better in terms of pressure stability. At the same time, this new device is smaller and requires much less instrumentation, such as multimeters, pressure gauges, bellows, and photosensors, than a previous system [1] used to obtain comparable control stability for thermal metrology.

This new pressure controller is especially dedicated to the GCHPs, but it can also be connected to a generic pressure line for other metrological applications. One prototype has been connected to the temperature amplifier [2] operating in the GCHP laboratory at INRiM, and a second improved version is now working in the laboratories of LNE-INM/CNAM in St. Denis, France. Other controllers have been assembled or will soon be manufactured for several calibration purposes, both in temperature and pressure metrology.

The device has been totally designed, developed, and assembled at INRiM: from the mechanics to the electronics, from the computer interface to the software; all components have been designed and assembled for the specific purpose.

2 Pressure Controller

2.1 Operating Principle

The system (Fig. 1) uses several electro-valves interposed among calibrated volumes with different dimensions in order to realize known ratios. Considering two volumes V_i and V_j at the same temperature and containing the same gas, respectively, at the pressures P_i and P_j, by connecting them together, the resulting pressure P_f in both is

$$P_\mathrm{f} = \frac{P_\mathrm{i} V_\mathrm{i} + P_\mathrm{j} V_\mathrm{j}}{V_\mathrm{i} + V_\mathrm{j}} \tag{1}$$

Therefore, if one volume is smaller than the other, a small pressure change occurs in the bigger one, after they have been put in communication by opening the valve that separates them.

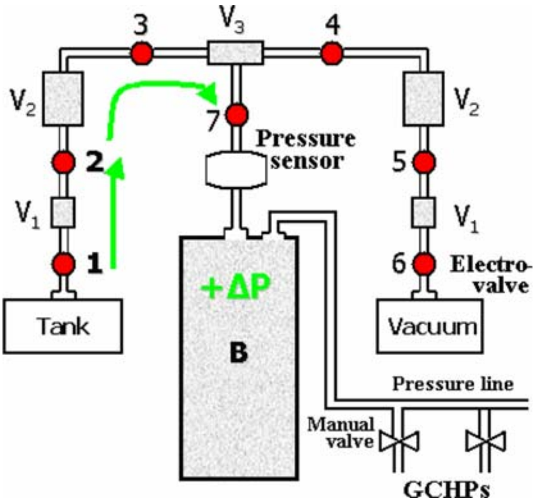

Fig. 1 Manifold for the pressure control system

Table 1 Pressure variations and the corresponding valve actions at 100 kPa

$\Delta p/p$	Pressure variation levels	Opening electro-valves sequence			
6×10^{-3}	1st	1–2	3–7		
2×10^{-4}	2nd	1–2	3	7	
6×10^{-5}	3rd	1	2	3–7	
2×10^{-6}	4th	1	2	3	7
-2×10^{-3}	1st	6–5	4–7		
-6×10^{-5}	2nd	6–5	4	7	
-2×10^{-5}	3rd	6	5	4–7	
-7×10^{-7}	4th	6	5	4	7

2.2 Mechanics

An innovative design, shown in Fig. 1, has been realized and developed at INRiM in order to obtain different pressure variations. The left and right sides are connected through electro-valves 1 and 6 to a tank and a vacuum pump, respectively, while a buffer volume of 50,000 cm^3 is connected between electro-valve 7 and the pressure line. The volumes are chosen as $V_1 = 1\,\text{cm}^3$, $V_2 = 100\,\text{cm}^3$, and $V_3 = 2\,\text{cm}^3$. Regarding this specific mechanical design, four levels of pressure variations can be performed for each side. The first level of pressure variation is obtained by opening electro-valves 1 and 2 (or 6 and 5 for the other side); immediately after these valves close, electro-valves 3 and 7 (or 4 and 7) are opened for about 1 s, then closed again. The finest pressure variation, corresponding to the fourth level, is obtained by opening and closing the electro-valves of the same side in a sequential way. In Table 1, the achievable pressure sensitivity evaluated with Eq. 1 is reported, together with the corresponding valve actions for each level of pressure variation. By operating the correct electro-valve openingclosing sequence, the whole system reaches the finest control capabilities.

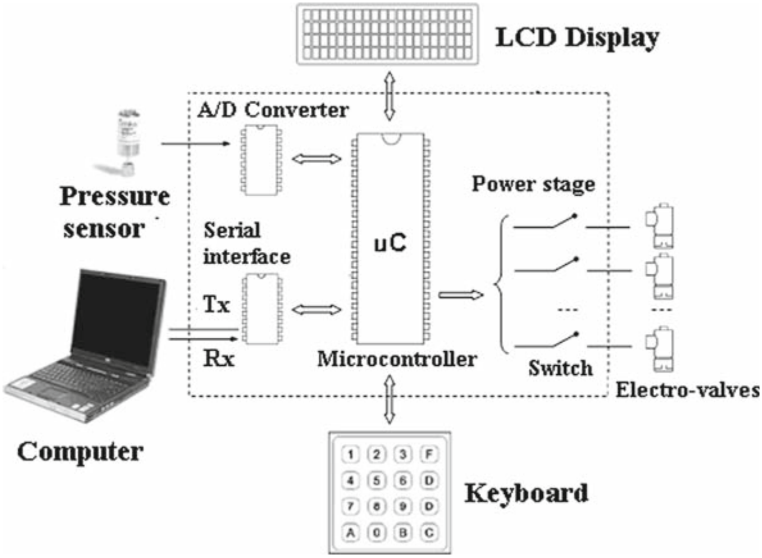

Fig. 2 Block diagram of the electronics involved in the pressure controller

2.3 Dedicated Electronics

The circuits have been designed to obtain automatic pressure acquisition and control at the best level achievable with the mechanical architecture and the physical principle previously described. The pressure sensor, with a relative sensitivity of 10^{-4}, is a capacitive transducer that is used to reach the pressure corresponding to a selected set-point value. The capacitance is converted into an analog voltage and sampled by a 24-bit analog-to-digital converter (ADC).

The micro-controller (μP), the main part of the system, accepts input from the analog-to-digital converter (ADC) and communicates with a display and a keyboard to set the parameters and display the data. The micro-controller compares the set-point pressure value with the current value and selects the correct electro-valve operating mode. Several PID subroutines are also implemented in the firmware of the micro-controller in order to reach the set-point value automatically.

The best control of the GCHP is achieved by using an SPRT as a temperature/pressure sensor with a relative sensitivity better than 10^{-6} in pressure. In this case, specific software was developed to read the SPRT with a resistance bridge, to evaluate the PID parameters, and to operate the electro-valves. A serial interface allows interfacing with a computer.

Figure 2 shows a block diagram of the electronics involved in the pressure controller.

3 Pressure Controller for the GCHPs

The GCHP is a special kind of heat pipe equipped with a gas line that enables direct control of the inner pressure. It can be connected to the pressure line, for instance, through a manual valve, as illustrated in Fig. 1. An inert gas is used to control the vapor pressure of the working fluid. The gas needs to have a different density from that of the vapor of the working fluid, in order to generate an interface between the two.

The measurement of the liquid–vapor phase-transition temperature is then obtained by means of SPRTs inserted in the thermowells. From the Clausius–Clapeyron equation and from the ideal gas law,

$$\frac{\mathrm{d}T_\mathrm{i}}{T_\mathrm{i}} = \frac{RT_\mathrm{i}}{ML}\frac{\mathrm{d}P_\mathrm{v}}{P_\mathrm{v}} \tag{2}$$

where R is the universal gas constant, T_i is the liquid–vapor interface temperature, M is the molar mass of the vapor, L is the latent heat of vaporization, and P_v is the vapor pressure. According to the Pictet–Trouton rule, $ML \approx 10\mathrm{R}T_\mathrm{b}$, where T_b is the boiling point of the working fluid; the factor RT/ML can then be approximated as $0.1T/T_\mathrm{b.}$ Since the GCHPs are generally operated in the pressure region between about 5 kPa and 500 kPa, which corresponds to a temperature variation within ±20% of the boiling point, Eq. 2 may be approximated as

$$\frac{\Delta T}{T} \cong 0.1\frac{\Delta P_\mathrm{m}}{P_\mathrm{m}} \tag{3}$$

Thus, a pressure variation results in a corresponding temperature variation.

The finest control achievable in pressure and temperature is obtained by means of an SPRT. The communication between the computer, the software, and the pressure controller allows a new concept in pressure control: the use of the SPRT as a pressure sensor (Fig. 3). In this case, the set point is no longer a pressure value, but a temperature (by means of a resistance set point). Once the set point has been defined, the computer, via a resistance bridge, interrogates an SPRT located inside the thermometer well of one GCHP. The software compares the resistance value to the set-point value and configures the electro-valves appropriately to control the pressure. The smallest pressure variation achieved with the controller is less than 1 ppm, and the temperature stability can therefore be kept around this relative value.

The quantity under control is the temperature T of the liquid–vapor transition of the working fluid inside the GCHP, measured by means of a SPRT that translates the temperature values into resistance values. A simple way to realize control at a desired temperature set point as a resistance value R_sp is to compare it with the measured value $R(T)$ and supply a pressure difference to compensate the difference (proportional control). The thermal loading of the system does not allow the temperature to reach the set-point value. Improvement of the control efficacy can be obtained by implementing PID (proportional-integral-derivative) control (Fig. 4).

The high-level automation achieved is obtained by means of a series of data extrapolation and PID subroutines. The PID function is widely used in closed-loop systems since it is a general function that is easily adapted to many systems. Values are filtered in real time, and a *datalog* file is generated in order to record any event during the acquisition and control.

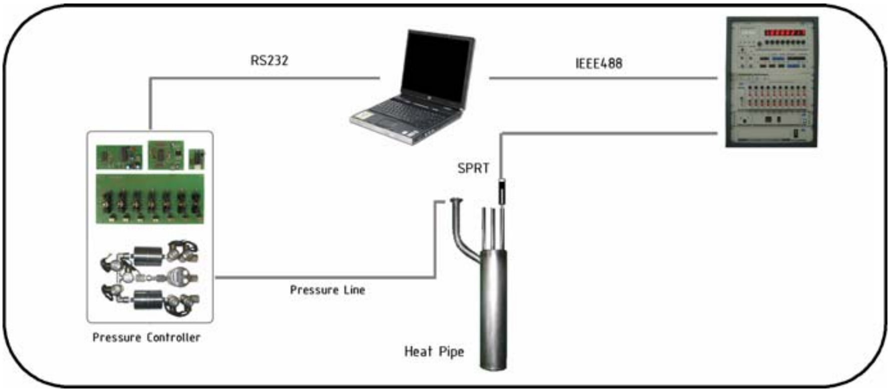

Fig. 3 Pressure control by means of an SPRT as the ‘pressure sensor’ and a resistance bridge

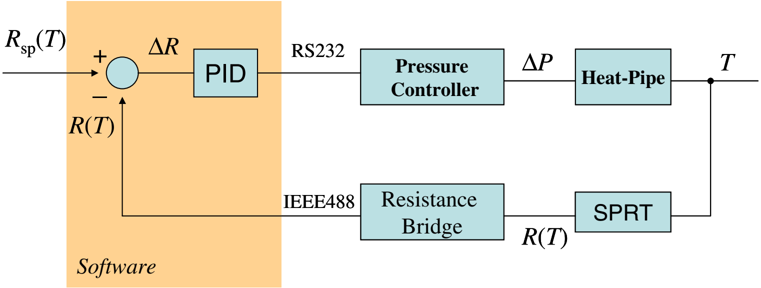

Fig. 4 Control loop diagram

This controller combines proportional control with two additional adjustments that help the unit to automatically compensate changes occurring in the system. By choosing the weights of the proportional, derivative, and integral terms, it is possible to configure the system for various requirements. The PID parameters can be determined by the software (auto-tuning), or manually.

The control parameters and the update time are chosen by investigating the system behavior and its physical characteristics throughout the whole operating range.

4 Software

The software [3] has been developed to allow complete control of the electronics, I/O interfacing routines, PID and auto-calibrating control functions, data acquisition modules, and the “real-time” control required to drive the electro-valves. Several forms and windows are used to maintain the pressure and temperature set points in a completely automatic way, keeping all the valuable information under the operator’s control.

The high-level automation achieved is obtained by means of a series of data extrapolation and PID subroutines. Time-dependent evaluation subroutines are continuously running, since the electro-valve actions can achieve “real-time” control within 10 ms. The temperature stability is estimated as the standard deviation of a series of measured resistance values. These values are filtered in real time and a datalog file is generated in order to record any event during the acquisition and control. Pressure and temperature values are continuously stored, together with all the significant information.

5 Results and Capabilities

The performance of the pressure controller has been evaluated using a GCHP filled with mercury, after the beginning of the phase-transition cycle. In this case, the pressure variation can be obtained by reading the temperature and using Eq. 3.

After the operator enters a set-point value, the program automatically evaluates the pressure difference that the pressure controller must supply. Initially, the gross regulation starts, using the capacitance pressure sensor until the set-point value is reached (Fig. 5). With this kind of pressure sensor, pressure stability within 50 Pa can be achieved; further improvement can be obtained by using an SPRT. The control algorithms allow reduced response times: in the initial phase, the system executes an auto-tuning process that allows the software to "learn" the behavior and the response to a specific action (i.e., a sequence of electro-valve openings). This auto-tuning consists of trying certain valve sequences and actions and waiting for the pressure to stabilize after the test sequence. After stability is reached, several parameters are evaluated in order to configure the correct actions in order to approach the desired value in as short a time as possible. Once the pressure value is being maintained close enough to the set-point value, the regulation is automatically switched to the SPRT, achieving a relative sensitivity better than 10^{-6} in pressure, for the finest control in order to maintain the set point. Thanks to the SPRT's sensitivity, the PID control, and the electro-valve system, the pressure stability is within 1 Pa throughout the whole operating range (Fig. 6), which corresponds to fractions of a millikelvin for temperatures between 100 °C and 450 °C using GCHPs operating with water, biphenyl, or mercury, and to the millikelvin level for higher temperatures between 450 °C and about 1,000 °C using GCHPs operating with potassium or sodium as working fluids.

Comparing this performance with the results achieved by other methods, the device presented here offers several advantages. First, this instrument is much less complicated than any other system adopted for similar investigations, such as the previous one operating at INRiM [1] or the one used by Hill and Gotoh [4]. It involves fewer devices, and no extra bath is required to keep the temperature of a reference volume as stable as possible. No motors are required, making for simpler maintenance and functioning. Also, the controller presented here can guarantee its capabilities continuously throughout the entire pressure range, not only at discrete pressures, as is the case when piston gauges are involved; it can also control the pressure for an unlimited time, which is not the case for systems where bellows are used. The operating range is also wider than both the previously mentioned systems.

These results allow several applications in thermal metrology, such as the calibration of SPRTs, HTSPRTs, industrial PRTs, and thermocouples by comparison. The same results support the operation of coupled GCHPs for the "Temperature Amplifier," a possible new temperature standard between the Al and Ag fixed points.

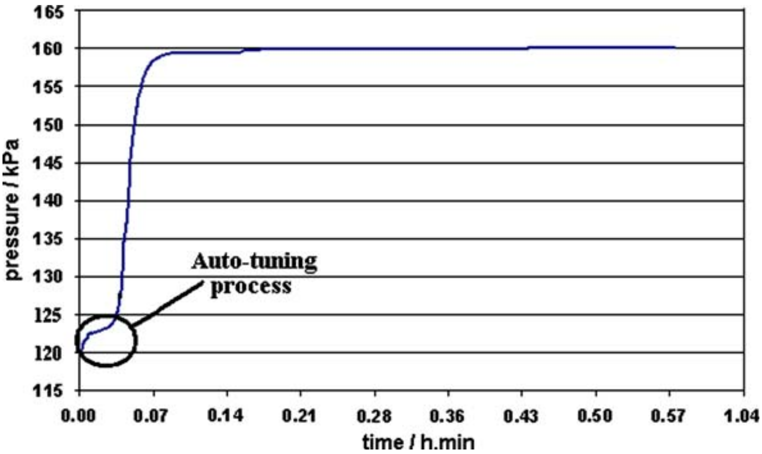

Fig. 5 Pressure change from 120 kPa to 160 kPa

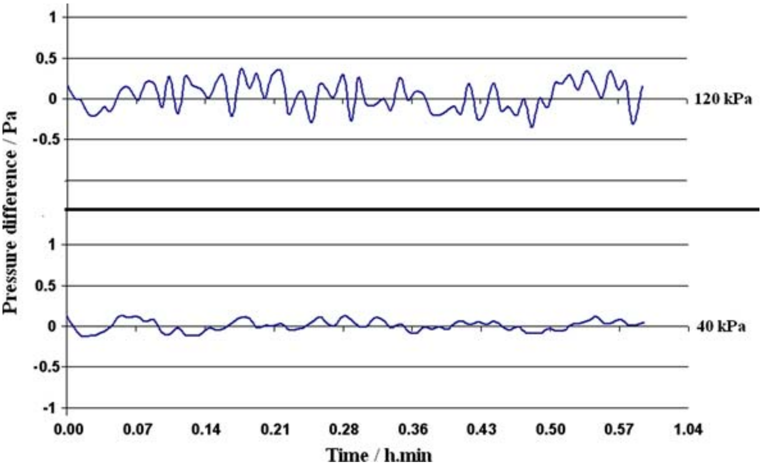

Fig. 6 Pressure control at 40 kPa, 120 kPa, and 390 kPa

6 Applications

Four pressure controllers have been assembled since February 2007. Since the first prototype (now used for the temperature amplifier), other models have been assembled both for research and calibration purposes. One was delivered to the LNE-INM/CNAM in St. Denis, France, for the pressure control automation of the GCHPs operating there. A second version will be used with a GCHP that operates with mercury, installed in the "calibration by comparison" Laboratory of INRiM where it will be used for the calibration of industrial PRTs and thermocouples. A further controller has been assembled and will be used by the Quality Center of the "Politecnico di Torino," where the device will be used for the control of a mercury-filled GCHP that will be devoted to the calibration of contact thermometers in the field between 240 °C and 400 °C. Another controller, equipped with a different pressure gauge operating up to 130 kPa, will be independent from the GCHP application and will be sent to the University in Cassino, Italy, for the calibration of pressure gauges; it will be used to control the pressure in a calibration line and will not use an SPRT or a resistance bridge. The electronics is now being implemented in order to make the system totally independent from any computer remote control.

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