Instrumentation with Computerized Data Acquisition for an Innovative Thermal Conductivity Apparatus

M. Kostic
Northern Illinois University
Error! Bookmark not defined., DeKalb, IL 60115, USA

Abstract. An innovative method and a novel research apparatus are being developed to measure the thermal conductivity of a non-Newtonian fluid while it is subjected to shearing flow, and to determine its dependence, if any, on shearing itself. This is contrary to the current state-of-the-art of measuring thermal conductivity under the condition of motionless fluid, to avoid convective heat transfer influence on the results. The emphasis here is given to the apparatus' instrumentation and computerized data acquisition design and its educational demonstration as a purposeful and typical application example, while a detailed description of the mechanical design and test results will be presented elsewhere.

The measurement and control are accomplished and integrated by using a computerized data acquisition system and a comprehensive virtual instrument, developed using the LabVIEW application software. The designed system accomplishes the following objectives: (a) acquire measured data with high speed and accuracy; (b) interactively process/analyze measured data for immediate use or store it for future post-processing; (c) provide interactive and accurate, feed-back process control - motor speed and guard-heating power, and (d) interactively display data in graphical and/or numerical forms. In addition, this system allows for easy modification and enhancement of virtual (software) instruments by modification of software programs.

1. INTRODUCTION

It is known that high molecular polymeric solutions and other rheologically complex non-Newtonian fluids are affected by shearing flow: becomes fiber-like, non-uniform and non-isotropic. An innovative method and a novel research apparatus are being developed to measure the thermal conductivity of a fluid while it is subjected to shearing flow, thus measuring the thermal conductivity as a function of temperature and shearing parameters themselves [1-14]. Such measurements are essential because the fluid (changing) structure and anisotropicity are flow-induced and dependent. To increase control of the parameters and accuracy, the flow should be isometric (laminar and one-dimensional) and heat transfer should be only in the transverse direction to the fluid velocity, i.e., orthogonal to it, to prevent interference from convective heat transfer. The emphasis here is given to the apparatus' instrumentation and computerized data acquisition design and its educational demonstration as a purposeful and typical application example, while a detailed description of the mechanical design and test results will be presented elsewhere [15-16].

The measurement and control are accomplished and integrated by using a computerized data acquisition system and a comprehensive so called "virtual instrument," developed using the LabVIEW application software. The motor's rotational speed is measured by a tachometer-sensor and controlled by a voltage-varying DC motor through a built in, solid-state, servo power-amplifier circuitry. The main heater is powered and controlled by a high-quality DC power supply, while two guard heaters are powered by common AC power supplies, and controlled, including overheating protection, by the computerized system through solid-state relay switches. The computerized system hardware consists of a National Instruments' MIO plug-in data acquisition board, shielded cable assemblies, and a signal conditioning module with a cold-junction compensated terminal block for thermocouple signals.

2. INNOVATIVE THERMAL CONDUCTIVITY APPARATUS

As already mentioned, the emphasis here is given on instrumentation and computerized data acquisition of a thermal conductivity apparatus, while a detailed description of the mechanical design is given elsewhere [15, 16]. The apparatus, see Figs. 1, 2, and 3, consists of: (1) an innovative, concentric-cylinders thermal conductivity cell; (2) a high performance, variable controlled-voltage or -current, DC power supply for the main heater; (3) two common, variable-voltage, AC power supplies for the guard heaters; (4) a variable speed DC motor with drive and controller; (5) a constant temperature bath controlled by a high performance, digital immersion circulator; and (6) computerized data acquisition system with signal conditioning hardware and LabVIEW application software. Brief descriptions of selected important components and functions are given below.

Thermal Conductivity Cell: The actual geometry of an apparatus and test fluid sample consists of a circumferential narrow gap (see Fig.1), similar to the apparatus for viscosity measurements [3, 4]. In addition, the appropriate heat transfer flux in the transverse to test fluid flow direction is provided. The main test-section dimensions are: D/d=2.598/ 2.488 *in* , outer/inner cylinder diameters respectively, with the 0.055 *in* thick gap, filled with the test-fluid in-between. The inner-cylinder's in-the-test-fluid immersion length is 3.8 *in*. It is heated by three 1.3-*in*-diameter electrical-resistance heaters, the central main heater with height h=1.44 *in*, and the two remaining guard heaters of 0.78 *in* high each. The inner cylinder with the heaters assembly is stationary, while the outer cylinder rotates (thus suppressing the Reynolds vortices) generating the Couette type-laminar flow of the test fluid. The two guard-heaters are controlled in such a way to maintain uniform axial temperature in the central, main-heater region, so that the latter heat flux is virtually in the radial direction only. Due to absence of the test-fluid's radial and axial velocities in the main-heater test-section region, the heat flux through the test fluid there is virtually transferred by conduction mode only. Thus, the measurement of the test-fluid's thermal conductivity, while undergoing shearing flow, is achieved.

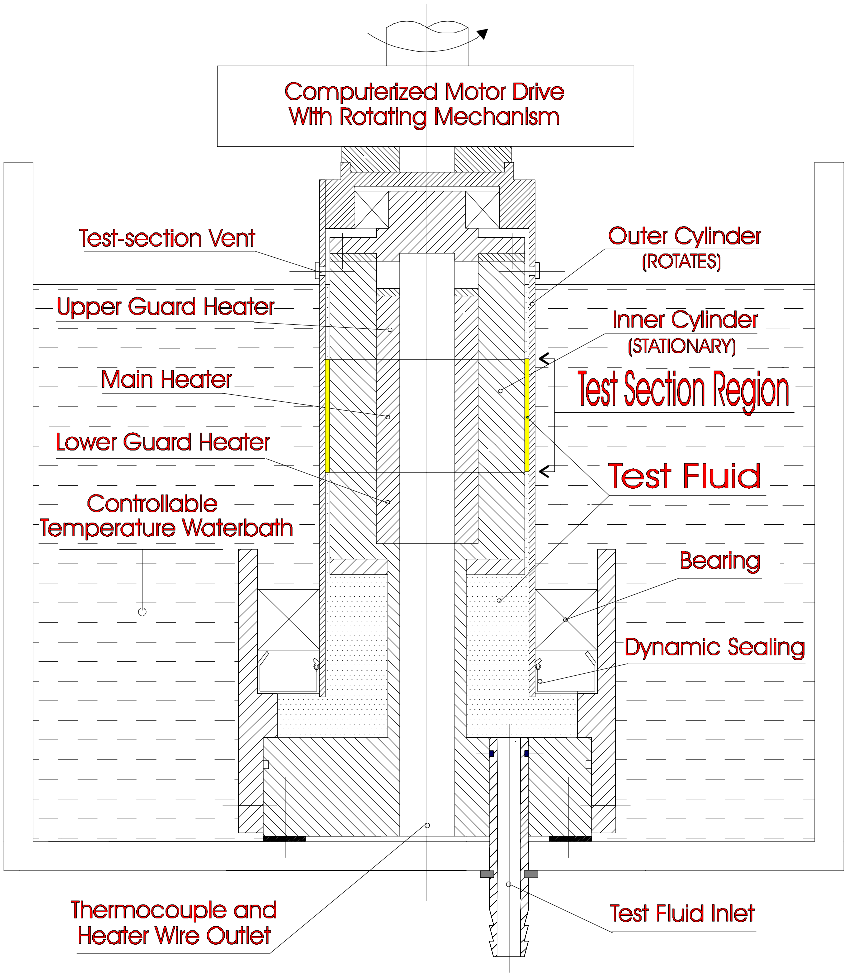

Fig. 1: A novel thermal conductivity apparatus

The directional fluid thermal conductivity *(k)* is calculated as the corresponding conductive heat transfer rate (Q_k) passing through the fluid test sample per unit of heat transfer area and per unit of appropriate temperature gradient, as a function of temperature level and the shearing rate:

$$k = C(Q_k/\Delta T) \tag{1}$$

where, $\Delta T = T_1 - T_2$ is the measured temperature difference and C represents an instrument constant depending upon the exact geometry of the thermal conductivity cell. If the constant C is determined from the geometrical characteristic of the fluid layer, the method is *absolute*. If the constant C is *calibrated* by using a standard fluid specimen with a known thermal conductivity, the method is *relative*. The thermal conductivity so determined corresponds to an average temperature level of $T = (T_1 - T_2)/2$. For a thermal conductivity cell of Figure 1 with guard heaters and

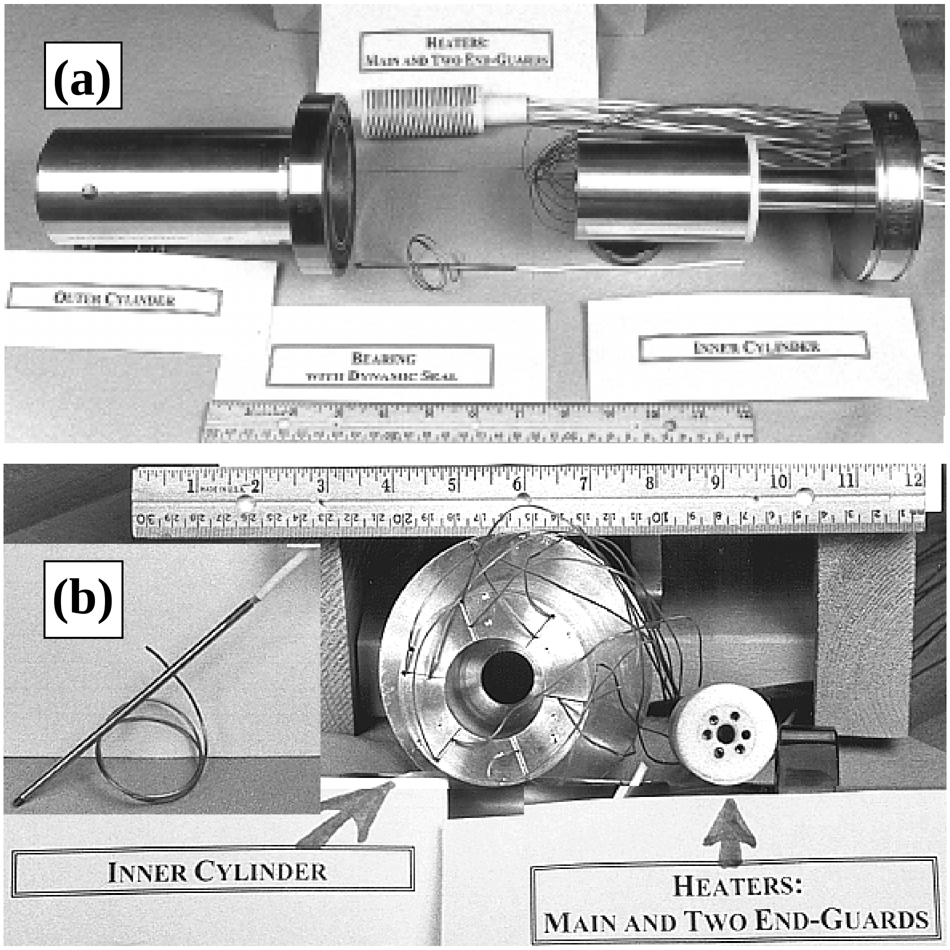

Fig. 2: Photograph of outer cylinder with bearing, heater element, and inner cylinder (a); top views of inner cylinder with thermocouples and heater element (b).

unidirectional radial heat flow, the constant *C* may be easily calculated, with the nomenclature given above, as:

$$C = ln(D/d)/(2\pi h) \tag{2}$$

Although the formula used to determined thermal conductivity from the measured quantities are simple (Eqs. 1 & 2), one should not be misled, due to the fact that the perfect conditions for which the equations are valid never exist, and many corrections must be applied, for example:

$$Q_k = (E \pm \Delta E)(I \pm \Delta I) \pm Q_r \pm Q_c \pm Q_{L.I} \pm Q_{us} \pm Q_{inh} \pm Q_{ch.r} \pm \ldots \tag{3}$$

where the electrical heater power *(E·I)* must be corrected for radiation *(r)*, free convection *(c)*, lead-in losses *(L.I)*, losses in heat flux due to unsteady state conditions *(us)*, inhomogeneities *(inh)*, possible chemical reaction *(ch.r)* between the fluid and the wetted surfaces, etc., respectively. Most of these corrections are very difficult, sometime impossible, to take into account. Therefore, in order to increase the accuracy of the measurements, the design of the thermal conductivity cell is such as to minimize those corrections. For example, the guard heaters will prevent end-effects/heat losses; proper material and surface finish will minimize radiation heat transfer; the thin gap will prevent free convection; accurate dimensions will minimize errors of the constant *C*; keeping minimal oscillations of the heating and cooling sources will minimize unsteady effects, etc. Also, due to fluid shearing motion (which may be beneficial - ironically and incidentally), the unwanted motion of the fluid particles in the heat transfer direction, i.e., in the orthogonal to the main (only) flow direction will be suppressed by virtue of the shearing itself.

Test Fluids and Results: Distilled water and standard Newtonian fluids with known thermal conductivity will be used for over-all calibration of the apparatus. Then, the thermal conductivity of the following non-Newtonian fluids, suspected to have shear-rate dependent thermal conductivity, will be measured as a function of shearing parameters: a) aqueous solutions of polyacrylic acid (Carbopol), b) aqueous solutions of polyacrylamide (Separan or Praestol), c) aqueous solutions of carboxymethyl cellulose (CMC), and d) aqueous solutions of polyethylene oxide (Poliox). At the time of this writing, the apparatus, including the instrumentation and data acquisition as described next, has been completed and used for educational demonstration. The project is in progress with the calibration of the apparatus being underway. However, the test results are not available yet, and will be presented after the completion of the project [15, 16].

3. INSTRUMENTATION AND MEASUREMENT

The required variables for thermal conductivity measurement are heat flux and temperature gradient through the test fluid, as well as the shearing rate of the test fluid. The apparatus' instrumentation is described next:

- The thermal conductivity apparatus is instrumented and equipped with twelve thermocouples imbedded in the inner cylinder at two different radial and five different axial locations (see Figs. 2 and 3). In addition, two thermocouples are attached to the outside surface of the outer cylinder, diametrically opposite at the center of the main-heater's axial location. These two thermocouples rotate with the outer cylinder and are terminated at its top-end with a quick four-wire connector. Due to this special circumstance, the outer cylinder temperature is measured after the steady state is achieved and after all other measurements are completed, by quick-stopping of the cylinder rotation and with the quick connector wired to the data acquisition system. Then, one more measurement of all other temperatures is performed to confirm the agreement with the corresponding measurements just before the quick stop. Due to the rotation of the outer cylinder, it is not known to the author if direct measurements of its temperature were done before. Two more thermocouples are used for measurement of constant temperature bath and room temperatures. All thermocouples are made from 30-gauge, T-type thermocouple wire and calibrated before and after assembly. These 16 thermocouples provide for the temperature gradient calculation needed for thermal conductivity measurement, and for confirming both, the unidirectional (radial only) heat flux through the test fluid and steady state thermal condition.

- The heat flux is measured through measurement of the DC voltage drop across the main heater and a precise current resistor (shunt), see Fig. 3.
- Finally, the fluid shear rate is calculated using the known test-section geometry and the measured rotational speed of the cylinder with a calibrated tachometer-sensor, see Fig. 3.

All measurements are repeated until the kinematics and thermal equilibrium is achieved. After that a number of final measurements are performed and results are obtained using statistical analysis, as described elsewhere [15, 16].

4. COMPUTERIZED DATA ACQUISITION AND CONTROL DESIGN:

(A Purposeful And Typical Application Example For Educational Demonstration)

Development and implementation of computerized data acquisition have the objectives of achieving more accurate measurement and interactive feed-back control and data reduction and presentation. The computerized data acquisition and control system is schematically presented in Fig. 3. It consists of the following components made by National Instruments:

- AT-MIO-16DE-10 data acquisition board (E Series architecture, 100 kSamples/sec; 12-bit analog inputs, 16 single-ended/8 differential channels; two 12-bit analog outputs; two 24-bit, 20 MHz counter/timers; 32 digital I/O channels);
- SCXI-1000 4-slot signal conditioning chassis;
- SCXI-1122 16-channel isolated transducer multiplexer and signal conditioning module for thermocouple sensors;
- SCXI-1322 shielded terminal block;
- SCXI-1353 shielded cable assembly.
- Two CB-50 terminal blocks with short NB-1 ribbon cables attached to appropriate SCXI-1353 shielded-cable assembly adapters for analog and digital input/output and counter/timer connections.

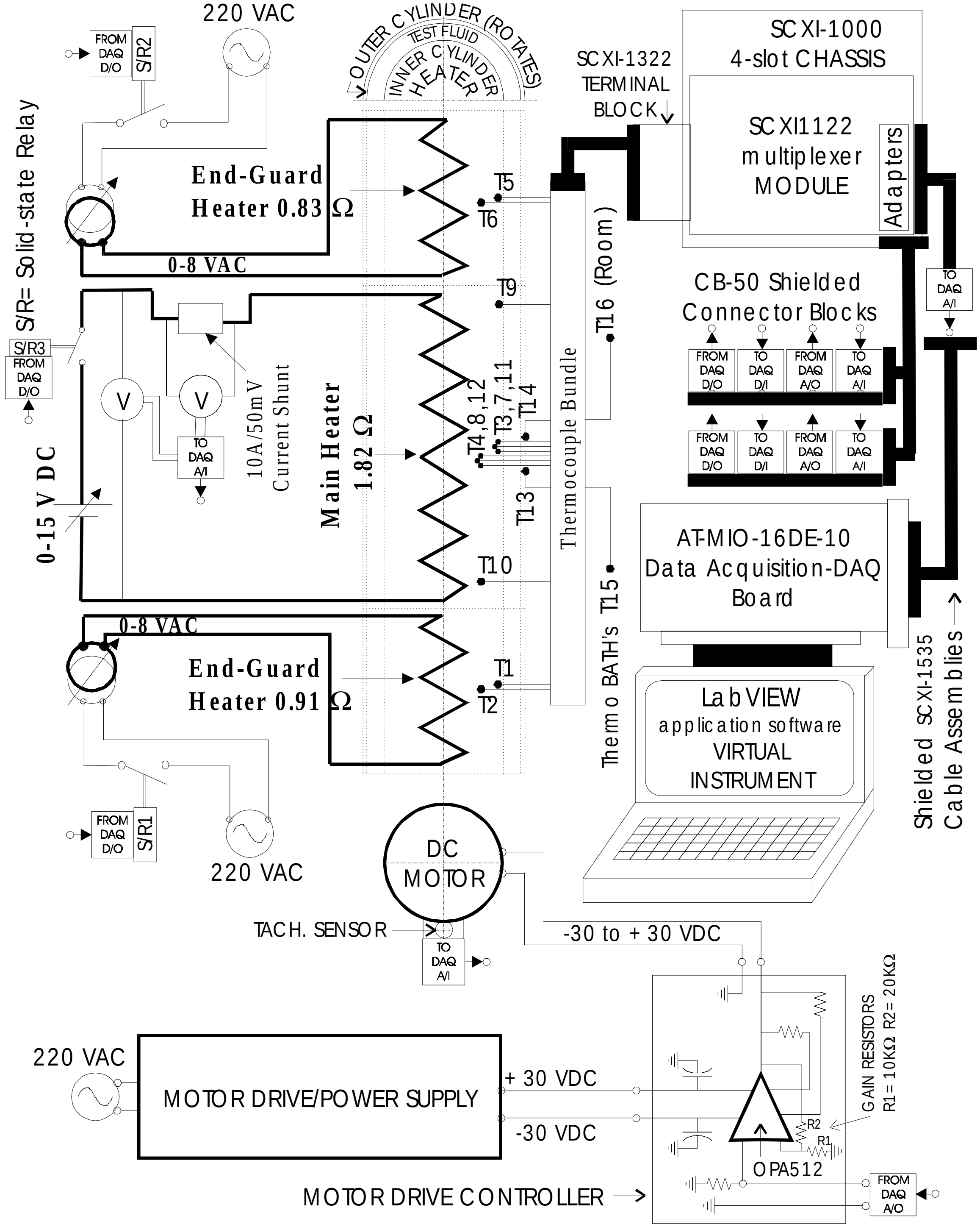

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Fig. 3: Schematic of Instrumentation and Data Acquisition with Control for Thermal Conductivity Apparatus

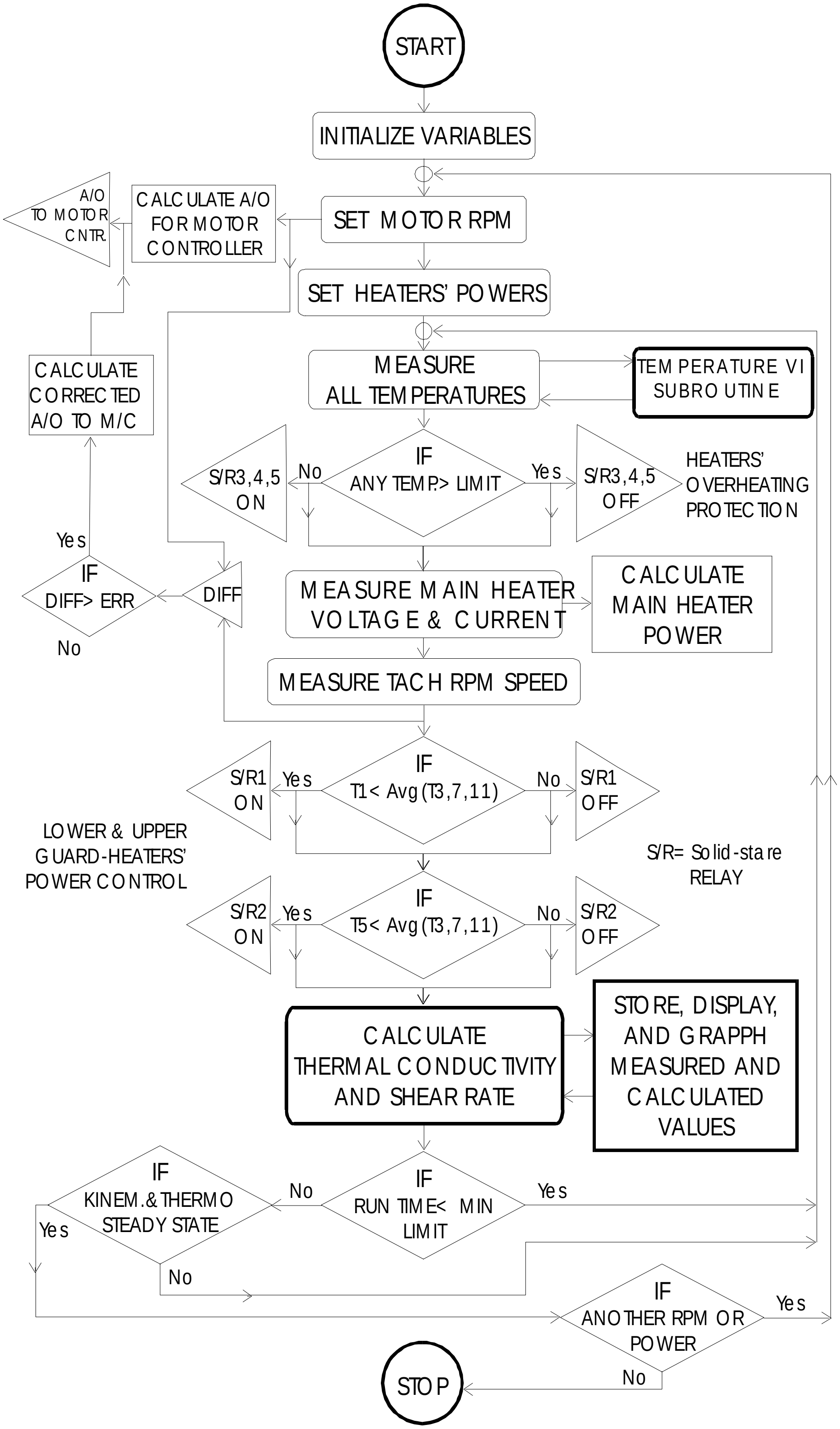

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Fig. 4: LabVIEW Virtual Instrument Algorithm for Thermal Conductivity Apparatus

A so called “virtual instrument” is developed, using the LabVIEW software application program. It integrates measurements, data acquisition, and interactive data processing and analysis for the feed-back control, and data and results display. The algorithm of the “Virtual Instrument” LabVIEW software program is presented in Fig. 4. The measurement and process control are enhanced by:

- implementing a feed-back control circuit for DC motor-drive using a calibrated tachometer-sensor;
- implementing solid-state relays for efficient and accurate feed-back control of guard-heaters’ power;
- comprehensive over-heating protection control;
- interactive and comprehensive monitoring for the kinematics and thermal steadiness of all processes; and
- convenience of increasing the number of thermocouple sensors for more advanced measurements of temperature gradients and heat fluxes.

This apparatus is enhanced with appropriate documentation and labeling to be used as a typical and elaborate application for educational demonstration in Engineering Experimental Methods I and II courses (MEE 390 and 490) at the Mechanical Engineering Department of Northern Illinois University (NIU). The basics of LabVIEW software are taught in these courses and students have used this apparatus as a purposeful application for demonstration of computerized instrumentation and data acquisition for interactive measurements and control. In addition to “seeing” the real-life demonstration of data acquisition hardware and software as described above, they are asked to write a small, simple LabVIEW programs to run a part of the apparatus components, like running the motor at desired rotational speed or programmatically varying the speed in harmonic or similar functional manner. The students are challenged to modify or write a new, creative LabVIEW programs (so called virtual instruments) in order to improve or enhance the existing measurement and process control or data analysis, and are made aware that functionality and quality of a virtual instrument is practically limited by our creativity.

5. CONCLUSION

One of the objectives of this project is to utilize the latest powerful, yet inexpensive, technological developments: sensors and transducers, data acquisition and control integrated boards, computers and application software, for research and teaching by example. The author has been introducing computerized data acquisition and reduction in engineering curriculum (starting with Experimental methods I and II courses at NIU) by using plug-in data acquisition boards and other hardware, and LabVIEW development and application software.

The designed, computerized measurement and data acquisition system, accomplishes the following objectives:

- acquire measured data with high speed and accuracy;
- interactively process and analyze measured data for immediate use or future post-processing;

- provide interactive and accurate feed-back process control - motor speed and guard-heating power, and
- interactively displays the raw/measured and processed/analyzed data in graphical and/or numerical forms.

In addition, such a system allows for easy modification and enhancement of so called “virtual (software) instruments” by modification of software programs.

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REFERENCES

[1] Sengers, J.V., and M. Klein, Eds., "Technical Importance of Accurate Thermophysical Property Information," *National Bureau of Standards Technical Note* No. 590, 1980.

[2] McLaughlin, E., "Theory of the thermal conductivity of Fluids," in R.P. Tye, Ed., *Thermal Conductivity*, Vol.2, Academic Press, London, 1969.

[3] Kostic, "New method and apparatus for thermal conductivity measurements of a fluid while in shearing flow," Invention Disclosure Draft, Northern Illinois University, 1992.

[4] Jimenez, J. and M. Kostic, "A Novel Computerized Viscometer/Rheometer," Review of Scientific Instruments Journal, Vol.65(1), p. 229-241, American Institute of Physics (1994).

[5] Bird and C. F. Curtiss, Fascinating polymeric liquids. *Physics Today*, p. 36-43, January (1984).

[6] Hartnett and M. Kostic, Heat transfer to Newtonian and non-Newtonian fluids in rectangular ducts. *Advances in Heat Transfer*, Vol.19, p. 247-356 (1989).

[7] Le Neindre, R. Tufeu, and A.M. Sirota. "Steady-State Methods for Thermal Conductivity," in *Measurement of the Transport Properties of Fluid* (Experimental Thermodynamics, Volume III, Edited by W.A. Wakeham, A. Nagashima, and J.V. Sengers), Intern. Union of Pure and Applied Chemistry, Blackwell Scientific, 1991.

[8] "Standard Test Method for Thermal Conductivity of Liquids," ASTM, Designation: D2717-78, 1978.?

[9] Assael et.al. "Transient Methods for Thermal Conductivity," in *Measurement of the Transport Properties of Fluid* (Experimental Thermodynamics, Volume III, Edited by W.A. Wakeham, A. Nagashima, and J.V. Sengers), Intern. Union of Pure and Applied Chemistry, Blackwell Scientific, 1991.

[10] Leidenfrost. "Measurement of Thermophysical Properties," in *Measurements in Heat Transfer, 2nd Edition*, Edited by E.R.G. Eckert and R.J. Goldstein, McGraw-Hill, 1976.

[11] Dutta and R.A. Mashelkar. "Thermal Conduction in Polymeric Liquids" in *Transport Phenomena in Polymeric Systems-I*, Special Editors: R.A. Mashelkar, A.S. Mujumdar, and M.R. Kamal (Advances in Transport Processes - Volume V), Wiley Estern Limited, 1987.

[12] Christiansen and S.E. Craig. "Heat Transfer to Pseudoplastic Fluids in Laminar Flow," *AIChE J.*, *Vol.8*, p. 154, 1962.

[13] Lee, Y.I. Cho, and J.P. Hartnett. "Thermal Conductivity Measurements of Non-Newtonian Fluids," *Lett. Heat Mass Transfer, Vol.8*, p. 255, 1981.

[14] Bellet, M. Sengelin, and C. Thirriot. "Determination of Thermophysical Properties of Non-Newtonian Liquids Using a Coaxial Cylindrical Cell," *Int. J. Heat Mass Transfer, Vol. 18*, p. 1177, 1975.

[15] Tong H., "Investigation of Thermal Conductivity for non-Newtonian Fluids as Function of Shear Rate," *M.S. Thesis in progress*, Northern Illinois University, DeKalb, IL, 1997.

[16] Kostic M. and H. Tong, "Innovative Thermal Conductivity Apparatus for Testing of Complex Fluids," Manuscript in progress, Northern Illinois University, DeKalb, IL, 1997.

MILIVOJE KOSTIC

Milivoje Kostic, Ph.D., P.E. is a Professor in the Department of Mechanical Engineering at Northern Illinois University. He received his Ph.D. in 1984 from the University of Illinois. Professor Kostic's teaching and research interests are Thermodynamics, Fluid Mechanics, Heat Transfer and related Fluid/Thermal/Energy sciences; with emphases on new technologies, experimental methods, creativity, design, and computer applications (**Error! Bookmark not defined.**).