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IEA
SOLAR R&D

INTERNATIONAL ENERGY AGENCY
solar heating and
cooling programme

Task III

PERFORMANCE TESTING OF
SOLAR COLLECTORS

Reference and calibration heaters

A compilation and evaluation of designs developed within IEA SH&C TASK III

January 1986

Swedish Council for Building Research

INTRODUCTION TO THE INTERNATIONAL ENERGY AGENCY AND THE IEA SOLAR HEATING AND COOLING PROGRAMME

The International Energy Agency was formed in November 1974 to establish cooperation among a number of industrialized countries in the vital area of energy policy. It is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD). Twenty-one countries are presently members, with the Commission of the European Communities also participating in the work of the IEA under a special arrangement.

One element of the IEA's programme involves cooperation in the research and development of alternative energy resources in order to reduce excessive dependence on oil. A number of new and improved energy technologies which have the potential of making significant contributions to global energy needs were identified for collaborative efforts. The IEA Committee on Energy Research and Development (CRD), supported by a small Secretariat staff, is the focus of IEA RD&D activities. Four Working Parties (in Conservation, Fossil Fuels, Renewable Energy, and Fusion) are charged with identifying new areas for cooperation and advising the CRD on policy matters in their respective technology areas.

Solar Heating and Cooling was one of the technologies selected for joint activities. During 1976–77, specific projects were identified in key areas of this field and a formal Implementing Agreement drawn up. The Agreement covers the obligations and rights of the Participants and outlines the scope of each project or "task" in annexes to the document. There are now eighteen signatories to the Agreement:

Australia	Italy
Austria	Japan
Belgium	Netherlands
Canada	New Zealand
Commission of the European Communities	Norway
	Spain
Denmark	Sweden
Federal Republic of Germany	Switzerland
	United Kingdom
Greece	United States

The overall programme is managed by an Executive Committee, while the management of the individual tasks is the responsibility of Operating Agents. The tasks of the IEA Solar Heating and Cooling Programme, their respective Operating Agents, and current status (ongoing or completed) are as follows:

Task I — Investigation of the Performance of Solar Heating and Cooling Systems – Technical University of Denmark (Completed).
Task II — Coordination of Research and Development on Solar Heating and Cooling – Solar Research Laboratory – GIRIN, Japan (Completed).
Task III — Performance Testing of Solar Collectors – University College, Cardiff, U.K. (Ongoing)
Task IV — Development of an Insolation Handbook and Instrument Package – U.S. Department of Energy (Completed).
Task V — Use of Existing Meteorological Information for Solar Energy Application – Swedish Meteorological and Hydrological Institute (Completed).
Task IV — Performance of Solar Heating, Cooling, and Hot Water Systems Using Evacuated Collectors – U.S. Department of Energy (Ongoing).
Task VII — Central Solar Heating Plants with Seasonal Storage – Swedish Council for Building Research (Ongoing).
Task VIII — Passive and Hybrid Solar Low Energy Buildings – U.S. Department of Energy (Ongoing).
Task IX — Solar Radiation and Pyranometry Studies – Canadian Atmospheric Environment Service (Ongoing).
Task X — Materials Research & Testing – Solar Research Laboratory, GIRIN, Japan (Ongoing).

Task III – Performance Testing of Solar Collectors

The overall goal of Task III is to develop and utilize, on an international level, common test procedures for rating the performance of a broad class of collectors for use in solar heating and cooling applications.

The original three subtasks were formally completed at the end of 1982:

Subtask A: Standard Test Procedures to Determine Thermal Performance
Subtask B: Development of Reliability and Durability Test Procedures
Subtask C: Investigation of the Potential of Solar Simulators

Upon their completion, the Executive Committee approved an extension of the Task for a period of three years and the addition of the following three subtasks:

Subtask D: Characterization of the Thermal Performance of Solar Collectors
Subtask E: Development of a Capability to Evaluate Domestic Hot Water System Performance using Short-Term Test Methods
Subtask F: Development of a Basis for Identifying the Performance Requirements and for Predicting the Service Life of Solar Collector System Components

The Participants in this task are: Australia, Austria, Belgium, Canada, Commission of European Communities, Denmark, Germany, Italy, Japan, Netherlands, Spain, Sweden, Switzerland, United Kingdom, and United States.

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Reference and calibration heaters

A compilation and evaluation of designs developed within IEA SH&C TASK III

Hans E B Andersson
Swedish Council for
Building Research, Sweden

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This report is part of the work of the IEA Solar Heating and Cooling Programme within

Task III: Performance Testing of Solar Collectors,

Subtask A: Development and Application of Standard Test Procedures for Determining Thermal Performance.

Swedish Council for Building Research, Stockholm, Sweden

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1. INTRODUCTION

During the early days of their round robin testing of solar collectors the participants of IEA Task III found considerable discrepancies between the efficiency data measured at different laboratories. The discrepancies were traced back to measurement errors in the quantities: fluid flow rate, temperature and solar irradiance.

At a meeting in Heidelberg in December 1978, therefore, a working group was set up to develop calibration procedures for the instrumentation used in testing (Ref. 1). At the same meeting W.B. Gillett proposed the use of an electrical reference heater, the purpose of which was to obtain an overall check of the calibration of the calorimetric part of the test facility. This instrument is here called a calibration heat source (CHS).

In the same period A. Pilatte reported the development of a calorimetric flowmeter with a similar design to that of the calibration heat source. This instrument is here called a reference heat source (RHS).

Since then, work has been done in several laboratories using heat sources either as flow meters or for calibration.

In a solar collector test facility there are four quantities that must be known for the computation of the collected heat power: the inlet and outlet temperatures of the heat carrying liquid, the mass flow of that liquid, and its specific heat capacity. The idea of a calibration heat source arose from the need for an quick overall check of the instrumentation used to measure these quantities. Thus an independent device was needed, having a good reproducibility.

In cases when the specific heat of the liquid was unknown or not constant over an extended period of testing time, a reference heat source could become a means of measuring the product of mass flow and specific heat, $\dot{m}c_p$. Alternatively, if $\dot{m}$ were measured separately, it could be used to obtain an in-situ measurement of c_p.

For high temperature applications it could be advantageous to let the reference heat source replace the fluid flow meter.

The reference heat source could also be used in a comparative mode, where the thermal efficiency of the collector were obtained by comparison with the reference heat source.

Experience has shown that the design of the heat source needs to be quite sophisticated. The intended accuracy of the measurement of collector efficiency is a few percent, and the accuracy of the RHS or CHS therefore should be better than that. Besides, the use of an RHS or CHS means making calorimetric measurements on a flowing liquid, which is not easy.

The aim of this report is to present a compilation of the work on reference and calibration heat sources within IEA Task III, and to evaluate the state of the art of the designs which have been used.

For the purpose of the evaluation, some mathematical procedures have to be employed. The RHS is physically similar to a solar collector, the main difference being the type of power input. Therefore it seems reasonable to use the efficiency function used in collector testing. Since the collector function does not usually include any dependence on fluid flow rate, this has to be added. A multiplication factor has proved useful for this purpose.

Seven heaters have been studied by Task III participants, and the data obtained are brought together and compared in this report. The data are analysed and fitted to several calibration functions in order to compare the efficiencies of the heat sources.

The CHS physically resembles a solar collector, but because of the lack of built-in temperature sensors and because of the way it is used, a mathematical treatment of its performance is not applied here: only a qualitative discussion is given.

2. PRINCIPLE OF THE HEAT SOURCES

2.1 The reference heat source

The reference heat source is an electrically-heated, well-insulated unit, through which a liquid is pumped whose inlet and outlet temperatures are measured.

The heat balance of the RHS may be written as

$$\dot{m}c_p.\Delta T = \eta.P_{el}, \tag{1}$$

where $\dot{m}.c_p.\Delta T = P_{th}$, the measured thermal power of the RHS, and where

$\dot{m}$ is the fluid mass flow rate,
c_p is the specific heat capacity of the fluid,
ΔT is $T_{out} - T_{in}$, the difference between the outlet and inlet temperatures of the fluid passing through the RHS,
P_{el} is the measured electric power input to the RHS, and
η is the efficiency of the RHS, defined as $\eta = P_{th}/P_{el}$.

2.2 The calibration heat source

The CHS, like the RHS, is an electrically-heated, well-insulated unit, through which a liquid is pumped. Unlike the RHS, the CHS has no thermometers installed for measuring the inlet and outlet temperatures of the liquid. These temperatures are measured using the thermometers of the test stand being checked.

The heat balance of the CHS may be written as

$$\dot{m}.c_p.\Delta T = P_{el} - P_L,$$

where $\dot{m}c_p$, ΔT and P_{el} have the same meaning as in 2.1, and P_L is the thermal loss of the CHS.

Since the CHS has no internal temperature sensors, the measurement of P_L is rather problematic. The use of the temperature sensors of the test facility will add the losses of the sensors to P_L.

Therefore P_L should be kept low enough to be negligible. Then a comparison between measurements of P_{el} and P_{th} in the test facility will give the measurement error, ε, of the test facility, as

$$\varepsilon = (P_{el} - P_{th})/P_{el}.$$

If P_L is not negligible the value calculated for the heat input of the CHS must be corrected using a separately-determined value of P_L.

The reduction of P_L to a negligible value can be obtained in different ways. One of the best is to use a 'thermal guard', which encloses the CHS and establishes an artificial environment of approximately the same temperature as the CHS. The guard may be heated by the heat-carrying liquid or by a separate electric heater that is regulated according to the temperature difference between the CHS and the guard.

3. THE USE OF THE HEAT SOURCES

The CHS is used to check the test facility calibration.

An RHS may be used for several purposes: measurement of the product of the flowrate of liquid and its heat capacity, measurement of specific heat capacity of fluid or, in the comparative mode, measurement of collector performance.

In high temperature applications, the RHS may be preferred because of its higher resistance to temperature compared with mechanical flow meters.

The heaters are usually used at reduced power rating to prevent local boiling of the fluid. There has been a tendency to reduce the volume of the vessel, to give the instrument a faster time response.

3.1 Calibration check

The CHS is placed in the position of the solar collector in the test rig. By comparing P_{th} and P_{el} a check of the facility calibration is obtained.

The thermal losses P_L are supposed small enough to be negligible.

3.2 Flow measurement

a) Fluid mass flow rate

From Eq. 1.

$$\dot{m} = \frac{\eta \cdot P_{el}}{c_p \cdot \Delta T} \quad (2)$$

The specific heat capacity of the fluid, c_p, must be known; the appropriate value is the mean value over the temperature range between T_{in} and T_{out}.

b) Heat capacity flow rate.

From Eq. 1.

$$\dot{m} \cdot c_p = \frac{\eta \cdot P_{el}}{\Delta T} \quad (3)$$

This application is useful when c_p of the fluid is unknown or when it is not constant over the time period of testing.

3.3 Specific heat capacity measurement

From Eq. 1,

$$c_p = \frac{\eta \cdot P_{el}}{\dot{m} \cdot \Delta T} \quad (4)$$

In this case $\dot{m}$ must be measured separately. The value obtained for c_p is a mean value for the temperature range between T_{in} and T_{out}. If a volumetric flow meter is used the product $c_p \cdot \rho$ is obtained, where ρ is the fluid density.

Note: When measuring $\dot{m}c_p$ or c_p, the temperature difference across the RHS should be kept large enough that it can be accurately measured, but small enough that the value obtained for $\dot{m}c_p$ or c_p applies to a reasonably narrow temperature range.

3.4 The comparison method

When connected in series with a solar collector the RHS may also be used in a comparative mode. The thermal efficiency of the collector, η_2, is found from

$$\eta_2 = \frac{\eta_1 \cdot P_{el}}{G\ A} \cdot \frac{\Delta T_2}{\Delta T_1}\ , \tag{5}$$

where

η_1 is the efficiency of the RHS,
P_{el} is the electric power input to the RHS,
G is the solar irradiance at the collector,
ΔT_1 is the temperature difference across the RHS,
ΔT_2 is the temperature difference across the collector, and
A is the collector reference area.

4. THE THERMAL EFFICIENCY OF THE RHS

By definition, the efficiency can be written as

$$\eta = P_{th}/P_{el}.$$

This η is usually a function of $\dot{m}$ and $\delta T = T_m - T_a$, where T_m is the mean temperature of the RHS, calculated as $T_m = (T_{out} + T_{in})/2$, and T_a is the ambient temperature. Since δT is a function of P_{el}, the efficiency also depends on P_{el}.

The measured thermal power P_{th} at the RHS can be written as

$$P_{th} = (P_{el} - P_L) \cdot f(\dot{m}), \tag{6}$$

where P_L is the thermal losses of the RHS and $f(\dot{m})$ indicates some function of the fluid flow rate $\dot{m}$. By rearrangement the efficiency, η, is found as

$$\eta = (1 - P_L/P_{el}) \cdot f(\dot{m}). \tag{7}$$

The thermal losses P_L may, as for the solar collector, be expressed as a first or second order polynomial in $\delta T = T_m - T_a$, and for the dependence on fluid flowrate a linear function in $(\dot{m})^q$ may be used, where q is a rational number. This gives

$$\eta = \left|1-k_1 \cdot \frac{\delta T}{P_{el}} - k_2 \cdot P_{el}\left(\frac{\delta T}{P_{el}}\right)^2\right| \left|k_3 + k_4 (\dot{m})^q\right| , \tag{8}$$

where the k's are regression coefficients. Experimental measurements made by IEA participants show that a linear function of $\dot{m}$ is satisfactory for the determination of η, a linear function of $\sqrt{\dot{m}}$ being an acceptable alternative.

Assuming a value of $q = 1$, Eq. 8 may be reduced to the following forms with first- or second-order polynomials in δT (the U's being regression coefficients):

$$\eta = U_1 + U_2 \frac{\delta T}{P_{el}} \tag{9}$$

$$\eta = U_1 + U_2 \frac{\delta T}{P_{el}} + U_3 P_{el}\left(\frac{\delta T}{P_{el}}\right)^2 \tag{10}$$

$$\eta = U_1 + U_2 \frac{\delta T}{P_{el}} + U_4 \dot{m} + U_5 \frac{\delta T}{P_{el}} \dot{m} \tag{11}$$

$$\eta = U_1 + U_2 \frac{\delta T}{P_{el}} + U_3 P_{el}\left(\frac{\delta T}{P_{el}}\right)^2 + U_4 \dot{m} + U_5 \frac{\delta T}{P_{el}} \dot{m} + U_6 P_{el} \left(\frac{\delta T}{P_{el}}\right)^2 \dot{m} \tag{12}$$

5. DESIGN REQUIREMENTS FOR THE HEAT SOURCES

The purposes of the RHS and the CHS were described in Sections 1 and 2. The design requirements will differ somewhat depending on the intended use of the heater. Some requirements though, are common to all uses of the heat source.

1 Low and well-defined thermal losses to improve the measurement accuracy and simplify calibration.

[Low losses mean that Eq. 9 is good enough for the RHS and that a liquid with well known c_p (water) can be used during calibration, independent of the liquid used in collector testing.]

2 Low power density on the heater element, to prevent local boiling in the transfer fluid.

3 Good fluid mixing ahead of the temperature sensors and around the heater element, to facilitate accurate measurement of temperature and temperature difference across the RHS.

4 Calibrated and carefully installed temperature sensors for the RHS.

5 Accurate measurement of electric power input.

For a CHS, one more requirement is important.

6 The ability, when checking the calibration of a collector test facility, to cover the whole range of temperature differences, ΔT and δT.

6. THE DESIGNS

Different design principles have been employed at different laboratories.

In the simplest case an electric heater element is mounted in a tubular vessel with an inlet and an outlet tube for the fluid flow, and with equipment for measuring the inlet and outlet temperatures. The vessel is surrounded by insulation material.

In other designs the tubular construction with heating element and temperature sensors are placed in a dewar vessel.

In some cases the effect of the insulation is enhanced by using a thermal guard ring.

All except one design are of a type which could be called once-through systems: that is, systems in which fluid passes the heater only once. One design has a loop with a circulation pump, to give the fluid a high flow rate across the heater.

6.1 University College, Cardiff

This CHS was the first one reported in Heidelberg in December 1978. Details of its design can be obtained from Ref. 2.

The heating element is a 6 kW 3-phase heater which is used in the power range 500 W to 3000 W. The power can be varied by using a variable transformer, and is measured by a calibrated watt meter.

6.2 National Bureau of Standards, Washington

In 1979, two proposed RHS designs were reported to the Task III experts (Ref. 3a). At that time, the first RHS had been built and the design of the second had been sketched out. Since then a third RHS, RHS No. 3, has been built and calibrated (Ref. 3b).

The RHS's are of the once-through type; the heater and the temperature sensors are placed in a narrow tube and the whole ensemble is stored in a dewar vessel which gives the insulation.

Some further details will be given for RHS 3. In this RHS the dewar vessel is combined with a thermal guard regulated by the inlet fluid. It has built in fluid mixing devices to ensure turbulent flow around the temperature sensors, and Pt100 resistance thermometers are employed to measure the absolute values of the inlet and outlet temperatures. The temperature difference between inlet and outlet is measured by a 10-junction type-T thermopile.

The heater is a cartridge heater sheathed in stainless steel. The power supply is a constant voltage transformer coupled to the RHS via a variable transformer.

The electric input power is varied between 530 W and 1750 W. A kWh standard is used to measure the electric input power to the RHS.

6.3 Centre de recherches sur l'energie solaire (CRES) Laboratoire de thermodynamique, Faculté Polytechnique de Mons

The vessel is a steel tube of diameter 75 mm and length 600 mm. A 3 kW 3-phase electric heater is used up to 1500 W.

The inlet flow is tangential and the tube has seven baffles to ensure turbulent flow.

Thermocouples are used to measure temperature, and the temperature difference across the RHS is measured by a 6-junction thermopile.

The RHS is installed in series with the solar collector and is used for fluid flow measurement (Ref. 4).

6.4 National Research Council, Ottawa

This RHS is of the once-through type. A 750 W immersion-heater element is enclosed in a copper pipe. A fluid mixing device and a temperature well are located at both the inlet and outlet of the heater. The components are connected in series and are surrounded by a thermal guard ring. Fibre glass is used to insulate the components from each other and from the guard ring. The guard ring utilizes the fluid entering the RHS at the heat source to limit the heat loss at high temperatures and the heat gain at low temperatures. The exterior of the guard ring is also insulated. An 8-junction type-T thermopile is used to measure the temperature difference across the RHS.

The RHS is intended for in-situ measurement of $\dot{m}c_p$ in a test loop and for the determination of solar collector efficiency by direct comparison (Ref. 5).

6.5 Thermal Insulation Laboratory, DTH, Denmark

This heater is an CHS and thus designed exclusively for the overall check of the calibration of the solar collector test facility.

A 1650 W heater element is enclosed in a stainless steel tube, which is insulated and surrounded by a thermal guard ring to minimize the thermal losses. The guard ring can be connected either up-stream or down-stream of the heater. The entire unit is placed in a box, filled with insulation material. The RHS is connected to the test facility, where it replaces the solar collector. The temperature difference across the RHS is measured using the thermopile that is usually used to measure the temperature difference across the solar collector (Ref. 6).

6.6. CSIRO, Australia

The CSIRO design is an RHS built as a circulating system with its own circulation pump. The flow rate in the loop is high enough to ensure turbulent flow.

The pipe has an inner diameter of 20 mm, and the loop has a length of 1147 mm.

The heater element is a heating tape wound round the outside of the tube. Its maximum power is 2000 W.

The fluids used are high-temperature oils.

The high-speed pumping in the circulation loop will introduce a significant amount of heat dissipation in the fluid. This heating is compensated by the heat loss from the heater tube and pump casing. By a suitable choice of insulation these two effects can be made to cancel one another. This method has been used when calibrating the device. (See Section 7.2 and Ref. 7.)

6.7 Switzerland

An RHS has been constructed at the Eidg. Institut für Reaktorforschung (EIR) at Würenlingen, Switzerland.

The RHS is of the once-through type. It employs a stepwise selectable heating element of 1, 2 and 3 kW electric input power. The temperatures are measured by two Pt100 temperature sensors. The unit, including the heating element and temperature sensors, is placed in a tank which is filled with insulation material. Its temperature range is from -50°C to +50°C and the intended heat transfer fluid is ethylene glycol (Ref. 8).

An RHS has also been constructed at Laboratoire de Thermique Appliquee/EPFL, Lausanne, Switzerland (Ref. 9). That RHS too is of the once-through type. It has 2 cartridge-type heaters of 1000 W each and is designed for use with synthetic oil (Marlotherm L).

7. CALIBRATION PROCEDURES USED AND ANALYSIS OF DATA SUPPLIED BY TASK III PARTICIPANTS

7.1 Introduction

A reporting format sheet was proposed by W. Gillett, and has been used by University College, Cardiff (United Kingdom), DTH (Denmark) and CRES, Mons (Belgium). Information from completed format sheets and from Refs. 2 to 8 are summarized in Table 1.

7.2. Performance data submitted for analysis

Calibration data were supplied by NRC, Canada; NBS, USA and CRES, Belgium.

DTH, Denmark supplied detailed test data for a case when the CHS was used for checking the accuracy of the test facility.

Data supplied for the Cardiff device included the losses of the CHS measured as a function of excess temperature over the ambient air. The measured losses were employed as correction terms when the CHS was used.

Data were supplied for the CSIRO device when used for measuring c_p in high temperature loops (+80°C to 300°C). The idea of the procedure is shown in Fig. 1. As described in 6.6, the mechanical power input from the circulation pump is more or less compensated by thermal losses. By applying two different insulations an equilibrium is obtained at two different temperatures, T_H, of the RHS. The equilibrium points are found by varying the mean temperature of oil in the heater at constant electric power input and mass flow rate, and measuring ΔT for a number of flow rates. The values of c_p computed (irrespective of η) form a number of curves which coincide at a certain temperature. At this temperature the net loss is zero and $\eta = 1$. The true value of c_p can be calculated from Eq. 4. The line through the two crossing points gives c_p as a function of temperature. Since the same flow meter is used both when measuring c_p and when testing solar collectors, an error in flow rate will be compensated by an error in c_p - provided the error in flow rate is constant.

7.3 Analysis of the data

From the available calibration data, the following quantities have been used to perform calculations:

electric input power,
excess RHS temperature above ambient,
fluid flow rate,
efficiency, defined as P_{th}/P_{el}.

Firstly several forms of Eq. 8 were used, where q was given the values 0.1, 0.5, 1.0 and 2.0, and functions with and without the second-order term in $\delta T/P_{el}$ were studied. It was found that the most useful functions were those of Eqs. 9 to 12. The calibration data are plotted in Figs. 2 a-c as functions of $\delta T/P_{el}$.

The thermal efficiency η in Eqs. 9 through 12 is a function of 3 independent variables: P_{el}, δT and $\dot{m}$. These measured variables are used to define up to 5 computed variables, which in turn are used in the curve fitting of the η functions. Table II shows the extreme values of the measured variables.

For the NBS and the NRC equipment, all the supplied data sets were used. For CRES some data sets were excluded after the first trials, the reason being large scatter about the regression curve.

Calibration data and detailed results of the fitting procedure are shown in Table III. For each instrument, the results obtained from using the most appropriate calibration function are shown.

Standard deviations and correlation coefficients are given in Table IV.

7.4 Discussion of results

(a) Choice of RHS efficiency presentation

NRC: Eq. 9, which has a linear loss term, gives a reasonably good correlation. The correlation is not improved by the introduction of a second-order loss term (Eq. 10). The introduction of the flow-rate dependence (Eq. 11) improves the correlation, and reduces the scatter about the regression curve. Minor extra improvement is obtained by adding a cross-correlation term and including the second-order loss term (Eq. 12). Eq. 9 is the most suitable calibration function.

NBS: The standard deviation shows the same trend as that for the NRC instrument although it is about three times as large. The linear curve in Eq. 9 does not fit the data. The flow rate term in Eq. 11 makes a considerable improvement. This effect is much more marked than for the NRC instrument. The introduction of the second order loss term gives a substantial non-linear loss dependence with $\delta T/P_{el}$. Eq. 11 is the most suitable calibration function.

CRES: This instrument shows a non-linear dependence on $\delta T/P_{el}$. The flow rate term gives some improvement but not as much as for the NBS-instrument. It should be noted that the fluid flow rates are all within a rather narrow range, 0.028 to 0.039 kg/s and the result is of course valid only for those flow rates. Eq. 10 is a suitable calibration function.

(b) Significance of heat losses

The NRC instrument, having a thermal guard ring, exhibits a constant loss coefficient, while the NBS and CRES instruments have loss coefficients which depend on the temperature difference δT between the RHS and the ambient air.

Low losses give low sensitivity of η to variations in input parameters such as $(\delta T/P_{el})^2$ and $\dot{m}$.

All instruments have according to Eq. 10 a maximum value of η at a value of $\delta T/P_{el}$ different from 0. The hypothesis that the thermal losses are proportional to the excess temperature of the RHS over that of the ambient air implies that a single mean temperature has to be defined and measured to represent the whole RHS. The average of the inlet and outlet temperatures of the RHS is easily measured, but is not necessarily equal to the desired representative temperature.

(c) The significance of flowrate

The NBS-instrument shows a very strong dependence on flow rate, while this correlation is less pronounced for the NRC and even less for the CRES instrument.

Within the working range, an increase in fluid flow rate will increase the measured efficiency. This may partly be due to the fact that the power input to the liquid caused by the pressure drop across the instrument is not measured, and that this power input increases when the fluid flow rate is increased.

(d) Variations in efficiency

For the NBS and CRES instruments with electric input powers of 500 W - 600 W the η-function is nearly linear in $\delta T/P_{el}$. At higher input powers a non-linearity appears.

It would have been interesting to include data from higher input powers for the NRC instrument. One would expect the appearance of a non-linearity in the loss term.

For the CRES instrument a wider range of flow rates would have been of interest. The relatively low correlation of η with fluid flow rate could be an effect of the narrow flow-rate range.

The cross-correlation terms are of minor importance for the NRC and NBS instruments.

8. CONCLUSIONS

1. A suitably-designed RHS is a very useful device, which can be employed with confidence to measure fluid flow rate, fluid specific heat capacity, and collector performance.

2. A suitably-designed CHS is a useful device for carrying out a rapid check of the instrument calibrations in the fluid loop of a collector test facility.

3. To facilitate a simple and accurate calibration, an RHS should be designed to have losses which are as low as possible. For this purpose a dewar vessel or a thermal guard ring may be employed. There are reasons to expect different characteristics from instruments having these two types of insulation.

An RHS having losses which are so low that Eq. 9 can be used over the whole working range of the instrument will have a simpler and more accurate calibration.

A thermal guard can be kept close to the mean temperature of the instrument by passing the heat-carrying liquid through it or by separate electric heating.

4. The calibration of an RHS must cover the whole working range for all variables. This means that for Eq. 9 at least 4 calibrations points are needed: maximum δT and P_{el} and minimum δT and P_{el} in all combinations.

For Eq. 10, which is non-linear, 2 extra values for each variable should be used, e.g. $(T(max) + T(min))/2$ and $(P_{el}(max) + P_{el}(min))/2$. This makes in all 9 calibration points.

Higher order calibration curves require more calibration points.

The very low standard deviation for the scatter around the regression curves and the high correlation coefficients obtained, especially for the NRC and the NBS instruments, indicate that this type of function is useful as a calibration function for the reference heat source.

It is obvious that the amount of work that has to be done to calibrate and recalibrate the RHS is significantly reduced by using a first-order correlation. Therefore, the cost of running the RHS is correspondingly lower when a simple calibration function can be used. If a first-order correlation function cannot be used, the design of the RHS should be improved.

It is important to note, however, that the minimum numbers of calibration points given above are not enough to fully characterize an RHS or determine its calibration function. One might need 40 points or more to characterize a new device.

5. In theory the heat capacity of the RHS is of no importance since all measurements are made in steady state conditions. However, in practice, a fast time-response of the RHS is very useful, and the heat capacity of the RHS should therefore be minimized. This means that the fluid volume should be kept low, and also that the heat capacity of the insulation should be as low as possible.

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Table I - Specifications for the RHS designs.

	NBS	NRC	Cardiff	DTH	CRES	CSIRO	EIR	EPFL
Max. rating W	2000	750	3000	1650	3000	-	3000	2000
Norm. rating W	530, 1750	590	-	1650	0-1500	2000	1000-3000	500-2000
Volume ℓ	-	1.0	6	1.8	2.38	0.36		0,9
Power dens. on heater W/cm^2	13	4.0	-	1.0	1.4-4.1	2.8		1,25-5,0
Flow rate kg/s	0.0125-0.0505	0.00867-0.0520	0.03 -	0.007-0.167	0.0283-0.0394	0.015 -	0,08-0,14	0,005-0,167
Stability of:								
inlet temp. $^{o}C/h$	±0.03	±0.05 at 20 ±0.1 at 60	±0.05 at 20 ±0.05 at 60	- -	±0.1 at 20 ±0.1 at 60	-		
outlet temp. $^{o}C/h$		±0.1 at 20 ±0.1 at 60	±0.20 at 20 ±0.20 at 60	- -	- -	- -		
fluid flow rate	±0.5 %	±0.5 %	±1.0 %	±1.0 %	±0.5 %	-		± 1 %
Accuracy of:								
ΔT	±0.05 ^{o}C	±0.02 ^{o}C	±1.0 %	-	±1 %	±0.05 %		
El. power	±0.1 %	±0.2 %	±1.5 %	±0.5 %	±1 %	-		± 0,01 %
Flow metering	grav. ±0.5 %	-	±2 %	±1.0 %	-	-		± 1 %
$\dot{m}$	-	-	-	-	-	-		
c_p	-	-	-	-	-	-		
$\dot{m}c_p$	-	-	-	-	-	±0.07 %		
Temp. range ^{o}C	-	-	-	0-100	-	80-300	-5 -+50	
ΔT ^{o}C	2.6-39.1	2.7-17.6	1.1-12.4	0-11.9	0.01-13.4	>50		
Dist. inlet-outlet	-	-	-	1 m	-	1.61 m		

Table II - Extreme values of measured variables.

	Min δT ^{o}C	Max δT ^{o}C	Min P_{el} Watts	Max P_{el} Watts	Min $\dot{m}$ kg/s	Max $\dot{m}$ kg/s
NRC	-7.6	59.9	579	593	0.008	0.052
NBS	1.1	65.7	511	1765	0.010	0.051
CRES	-6.2	52.3	500	1500	0.028	0.039

Table IIIa - NRC-data fitted to Eq. 9.

U_1=1.0005 U_2=$-9.2242 \cdot 10^{-2}$

	Flow rate	El power	T_m-T_a	η_m(meas)	η_c(calc)	$\eta_m - \eta_c$
1	0.00865	581.55	1.01	1.002	1.000	0.002
2	0.00826	579.47	21.37	0.994	0.997	-0.003
3	0.00792	590.77	40.46	0.989	0.994	-0.005
5	0.01681	592.82	-4.22	0.998	1.001	-0.003
6	0.01648	591.81	17.06	0.997	0.998	-0.001
7	0.01666	590.73	36.73	0.995	0.995	0.000
8	0.01624	589.00	57.90	0.991	0.991	-0.000
9	0.02478	592.93	-6.00	1.001	1.001	-0.000
10	0.02533	580.38	16.11	1.001	0.998	0.003
11	0.02455	591.15	35.34	0.996	0.995	0.001
12	0.02483	588.50	56.90	0.988	0.992	-0.004
13	0.03382	593.23	-6.86	1.000	1.002	-0.002
14	0.03364	592.33	14.13	0.999	0.998	0.001
15	0.03328	582.59	33.52	0.997	0.995	0.002
16	0.03298	588.61	57.43	0.993	0.992	0.001
17	0.05161	583.48	-7.58	1.000	1.002	-0.002
18	0.05039	580.67	14.39	1.004	0.998	0.006
19	0.05022	581.70	33.57	1.000	0.995	0.005
20	0.05033	579.43	59.14	0.996	0.991	0.005

Standard deviation = 0.00310

Correlation coeff. = 0.76478

Table IIIb - NBS-data fitted to Eq. 11.

U_1=0.9771 U_2=$-1.5417\cdot10^{-2}$ U_4=0.50791 U_5=-0.36537

	Flow rate	El power	T_m-T_a	η_m(meas)	η_c(calc)	$\eta_m-\eta_c$
1	0.01248	531.70	5.18	0.985	0.983	0.001
2	0.03750	530.80	1.70	1.003	0.996	0.007
3	0.05022	525.10	1.10	1.019	1.003	0.016
4	0.01238	1747.30	18.50	0.985	0.983	0.002
5	0.02524	1743.20	10.30	0.993	0.990	0.004
6	0.02532	1740.50	9.70	0.994	0.990	0.004
7	0.03758	1735.50	7.80	0.997	0.996	0.001
8	0.05062	1734.30	6.20	1.001	1.003	-0.002
9	0.01286	529.60	22.90	0.989	0.983	0.006
10	0.02530	525.40	21.10	0.998	0.989	0.009
11	0.03737	523.70	20.10	1.001	0.995	0.006
12	0.04960	527.00	19.60	1.005	1.001	0.004
13	0.01236	1756.00	34.70	0.982	0.983	-0.001
14	0.02476	1753.90	27.70	0.993	0.989	0.003
15	0.02471	1745.20	27.90	0.991	0.989	0.001
16	0.02475	1765.20	28.40	0.991	0.989	0.002
17	0.03747	1732.20	25.30	0.994	0.996	-0.001
18	0.04906	1744.40	24.00	0.993	1.002	-0.009
19	0.04922	1728.90	25.40	0.994	1.002	-0.008
20	0.01203	518.80	44.90	0.982	0.982	0.000
21	0.01249	517.10	45.00	0.986	0.982	0.004
22	0.02432	514.10	43.10	0.990	0.987	0.003
23	0.03651	511.20	42.30	1.001	0.993	0.008
24	0.04889	532.20	42.10	1.007	0.999	0.008
25	0.01038	1747.00	58.60	0.975	0.982	-0.006
26	0.01041	1742.80	58.90	0.975	0.982	-0.006
27	0.02429	1756.80	48.70	0.981	0.989	-0.008
28	0.03661	1761.30	46.20	0.988	0.995	-0.007
29	0.04833	1756.70	45.20	0.989	1.001	-0.012
30	0.02388	513.30	60.30	0.984	0.986	-0.002
31	0.03678	526.30	59.30	0.988	0.993	-0.005
32	0.04839	525.60	62.20	0.997	0.998	-0.001
33	0.02440	1749.30	65.70	0.978	0.989	-0.011
34	0.03637	1725.10	65.60	0.984	0.995	-0.010

Standard deviation = 0.00640

Correlation coeff. = 0.72939

Table IIIc - CRES-data fitted to Eq. 10.

U_1=1.0216 U_2=0.52538 $U_3=-2.086\cdot10^{-2}$

	Flow rate	El power	T_m-T_a	η_m(meas)	η_c(calc)	$\eta_m-\eta_c$
1	0.02820	500.00	-6.22	0.996	1.013	-0.017
2	0.03320	500.00	11.64	1.029	1.028	0.001
3	0.02800	500.00	29.38	1.010	1.016	-0.006
4	0.03900	500.00	32.50	1.004	1.012	-0.008
5	0.03300	500.00	32.91	1.005	1.011	-0.006
6	0.02800	500.00	33.63	1.002	1.010	-0.008
7	0.03270	500.00	47.49	0.982	0.977	0.005
8	0.03930	1000.00	-4.86	1.014	1.019	-0.005
9	0.03330	1000.00	-4.68	1.016	1.019	-0.003
10	0.03920	1000.00	10.21	1.032	1.025	0.007
11	0.02800	1000.00	29.89	1.020	1.019	0.001
12	0.03900	1000.00	33.55	1.023	1.016	0.007
13	0.02800	1000.00	36.95	1.014	1.013	0.001
14	0.03270	1000.00	49.98	0.986	0.996	-0.010
15	0.03930	1500.00	-3.46	1.019	1.020	-0.001
16	0.03330	1500.00	-2.68	1.018	1.021	-0.003
17	0.02820	1500.00	-1.96	1.013	1.021	-0.008
18	0.02810	1500.00	17.48	1.021	1.023	-0.002
19	0.03320	1500.00	13.97	1.031	1.024	0.007
20	0.03920	1500.00	10.16	1.038	1.024	0.014
21	0.03900	1500.00	30.04	1.025	1.020	0.005
22	0.03900	1500.00	35.11	1.020	1.017	0.003
23	0.02770	1500.00	52.28	1.026	1.002	0.024

Standard deviation = 0.00862

Correlation coeff. = 0.78111

Table IV - Standard deviations and Correlation coefficients.

	Eq. 9		Eq. 10		Eq. 11		Eq. 12	
	Stand. dev.	Corr. coeff.	Stand. dev.	Corr. coeff.	Stand. dev.	Corr. coeff.	Stand. dev.	Corr. coeff
NRC	0.0031	0.765	0.0030	0.789	0.0019	0.920	0.0015	0.950
NBS	0.0093	0.133	0.0088	0.344	0.0064	0.729	0.0052	0.828
CRES	0.0115	0.549	0.0086	0.781	0.0108	0.623	0.0067	0.874

$$\text{Standard deviation} = \sqrt{\frac{\Sigma|\eta(\text{meas.})-\eta(\text{calc.})|^2}{N}}$$

$$\text{Correlation coeff.} = \sqrt{\frac{\Sigma|\eta(\text{calc.})-\eta(\text{meas.})|^2}{\Sigma|\eta(\text{meas.})-\eta(\text{meas.})|^2}}$$

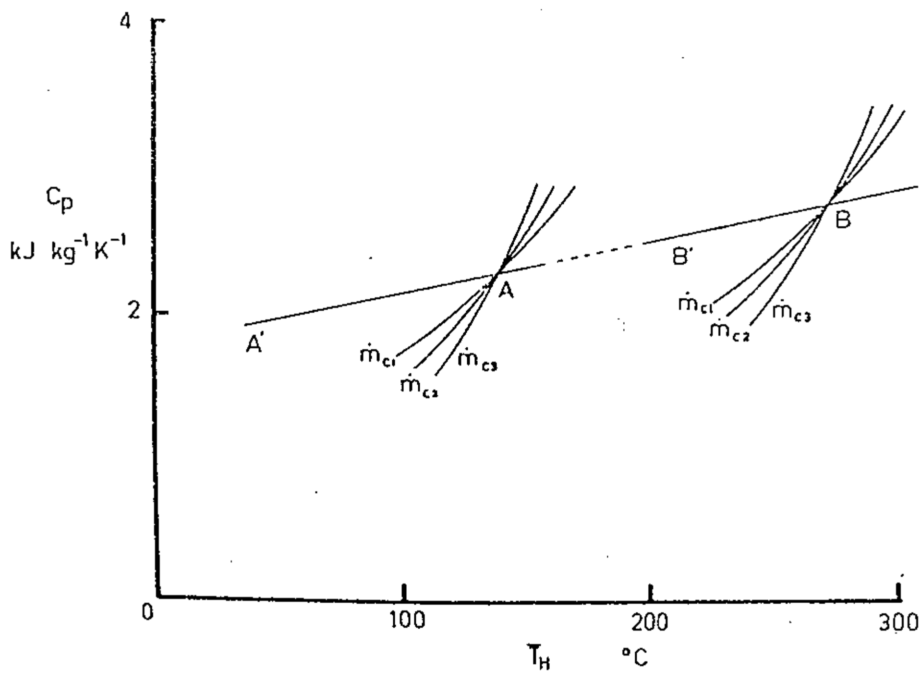

Fig. 1 - CSIRO. Deviation of c_p as a function of $\bar{T}_H = (T_{in}+T_{out})/2$

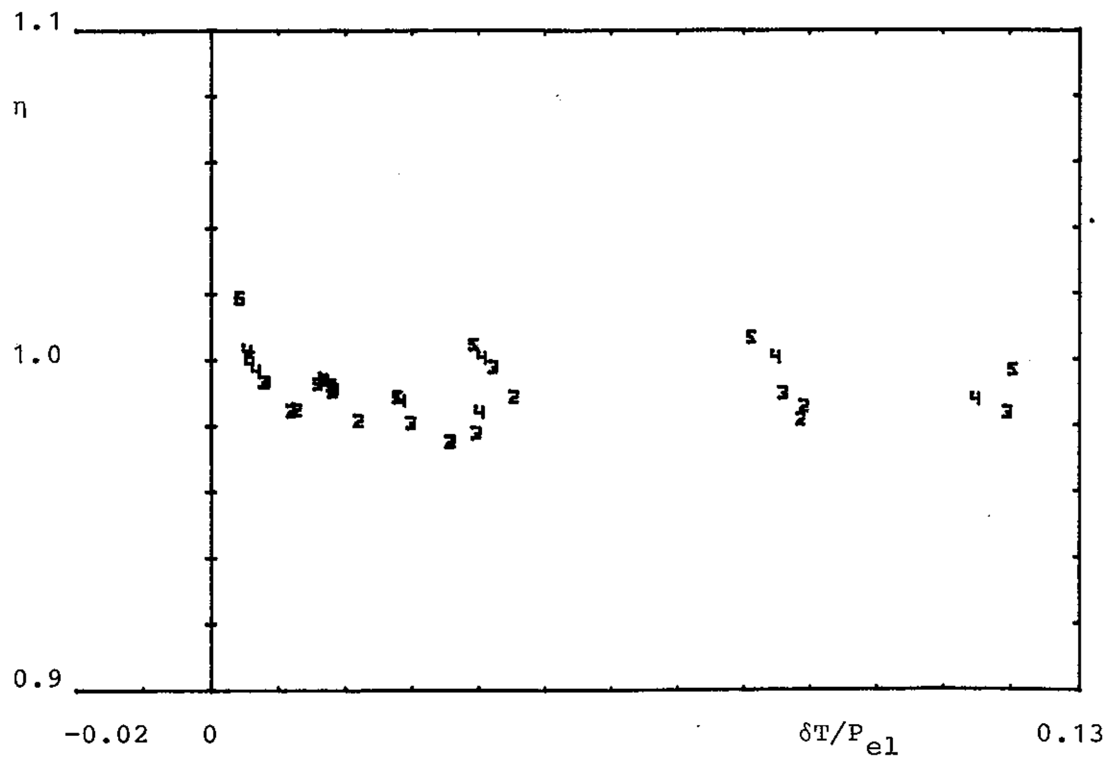

Fig. 2a. - NBS. η v.s. $\delta T/P_{el}$. The numbers are related to fluid flow rate as follows.

	$\dot{m} \le 0.01$ kg/s	1
0.01<	$\dot{m} \le 0.02$ "	2
0.02<	$\dot{m} \le 0.03$ "	3
0.03<	$\dot{m} \le 0.04$ "	4
0.04<	$\dot{m} \le 0.05$ "	5
0.05<	$\dot{m} \le 0.06$ "	6
0.06<	$\dot{m} \le 0.07$ "	7
0.07<	$\dot{m} \le 0.08$ "	8

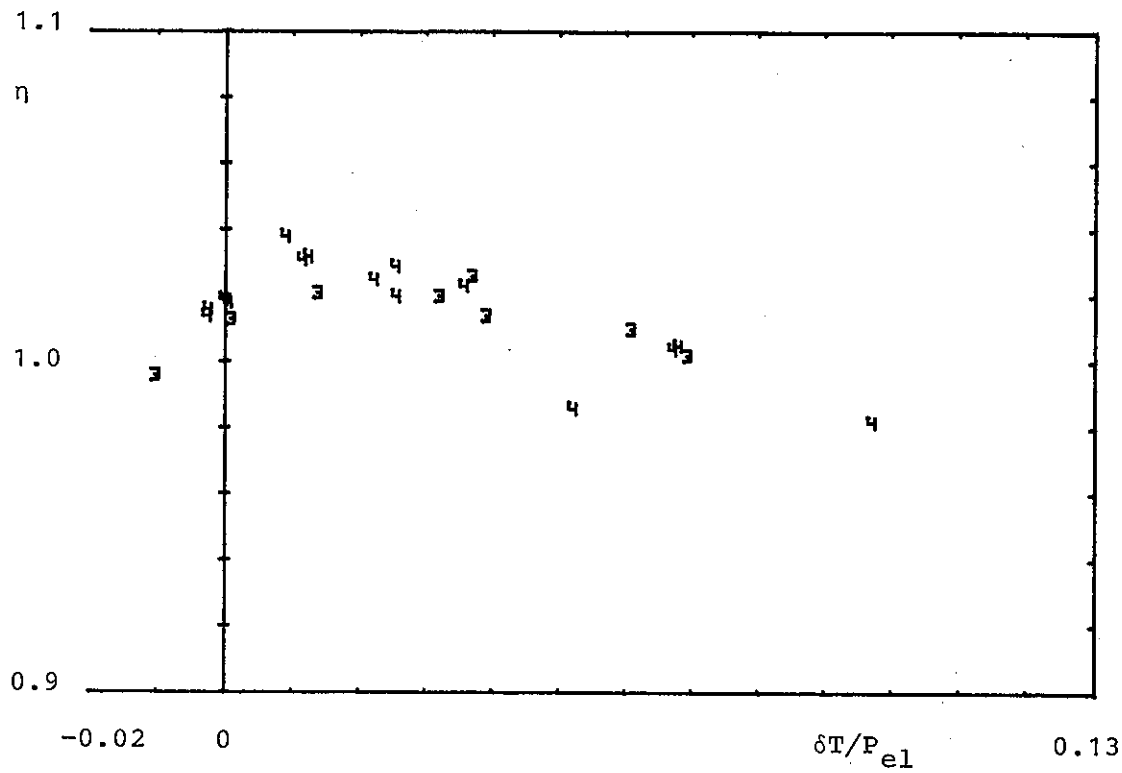

Fig. 2b. - CRES. η v.s. $\delta T/P_{el}$. The numbers are related to fluid flow rate as given in Fig. 2a.

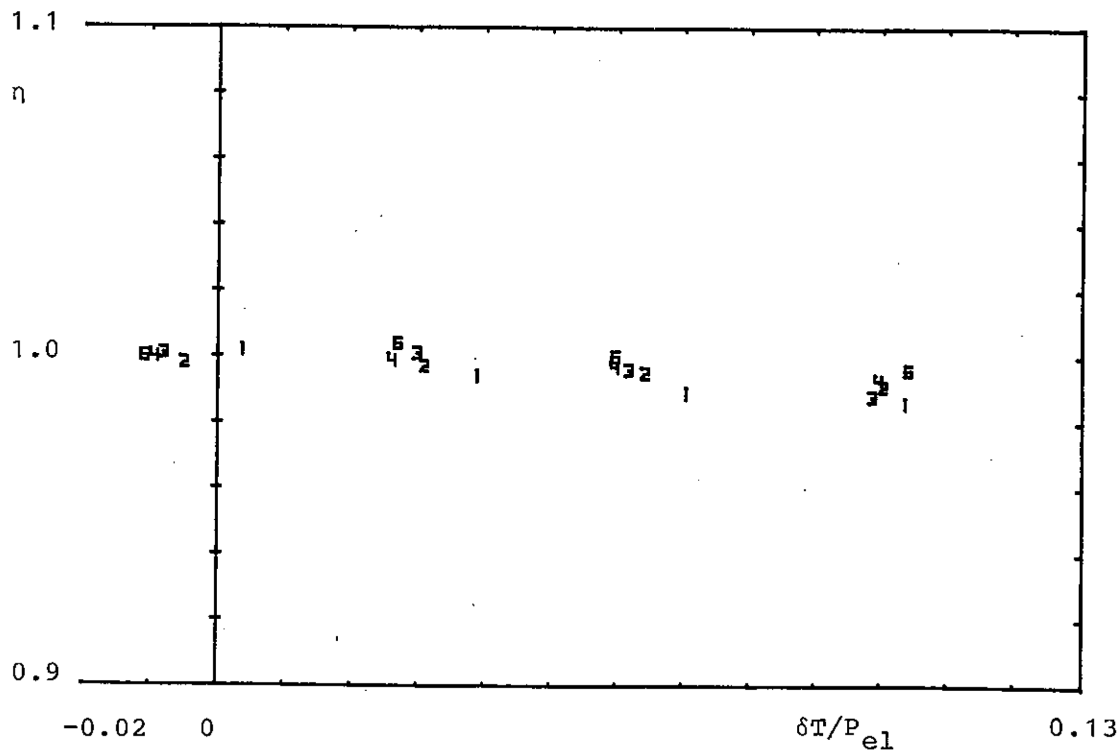

Fig. 2c. - NRC. η v.s. $\delta T/P_{el}$. The numbers are related to fluid flow rate as given in Fig. 2a.

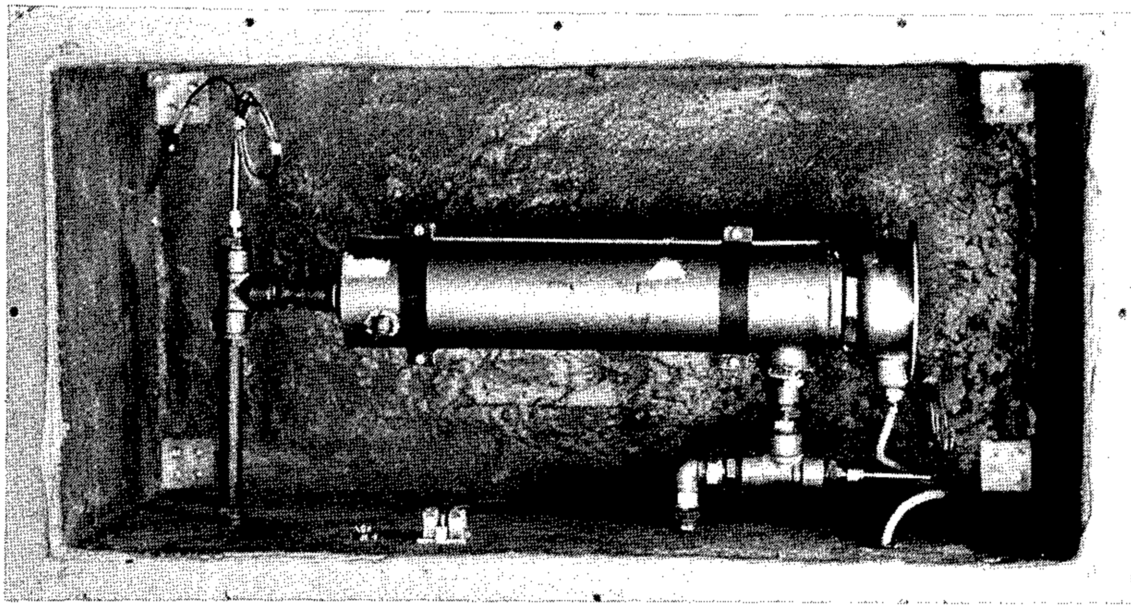

Fig 3 The CHS from University College, Cardiff

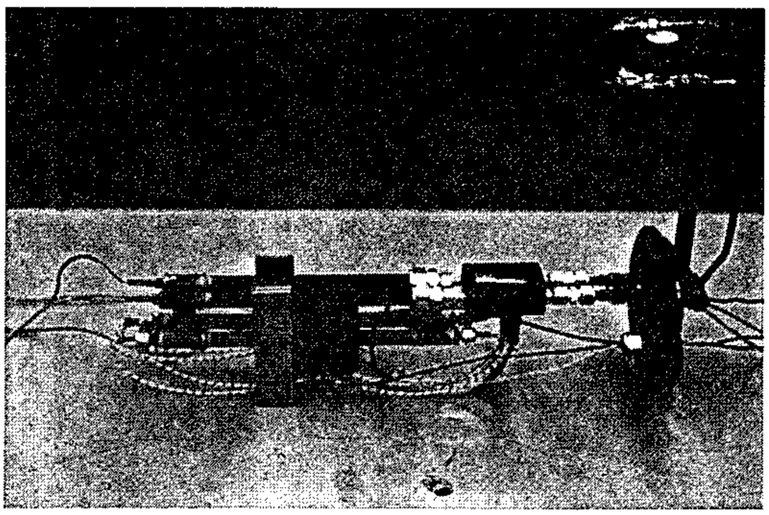

Fig 4 The RHS from National Bureau of Standards, Washington

Fig 5 The CHS from Thermal Insulation Laboratory, DTH Denmark

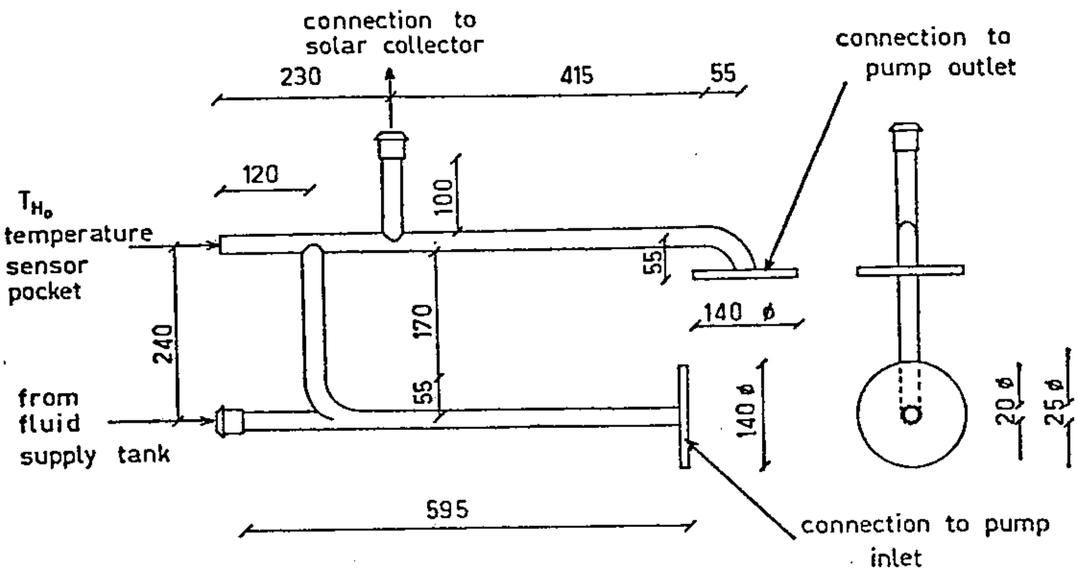

Fig 6 The RHS from CSIRO, Australia

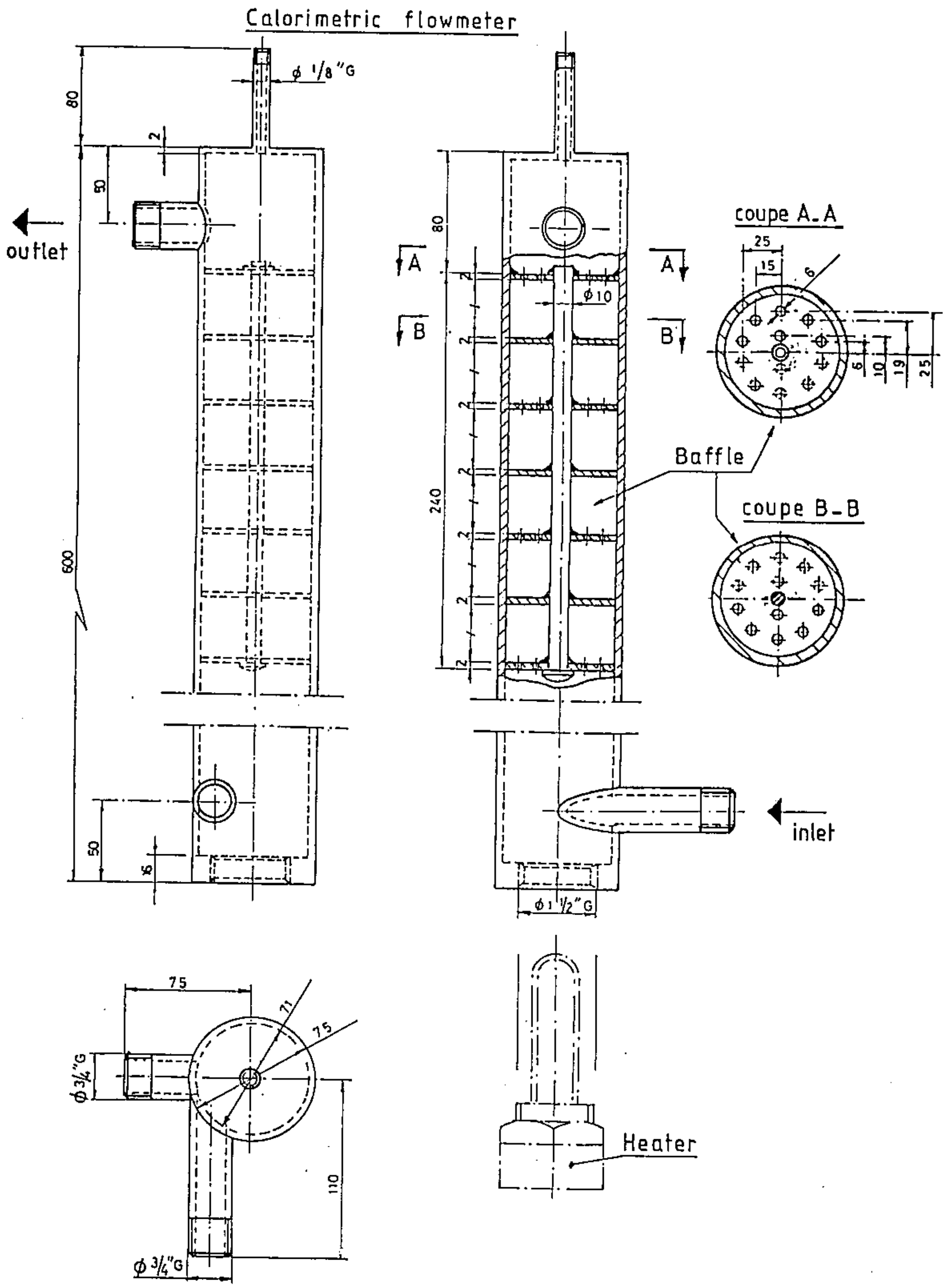

Fig 7 The RHS from Faculté Polytechnique de Mons

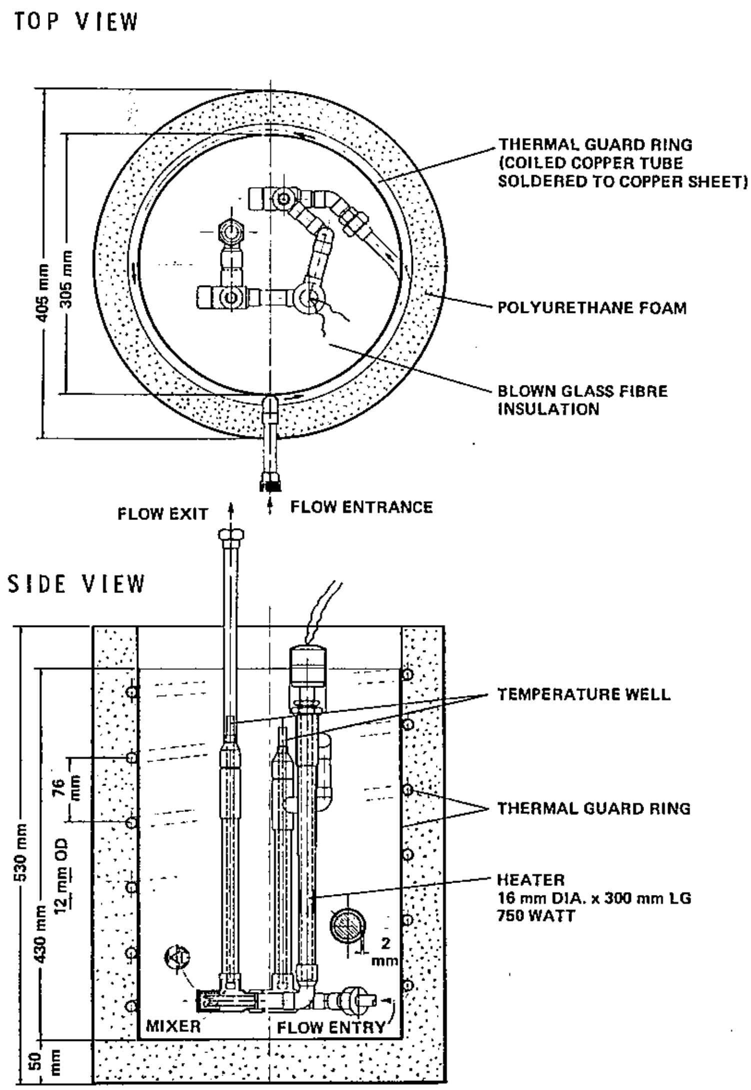

Fig 8. The RHS from National Research Council, Ottawa

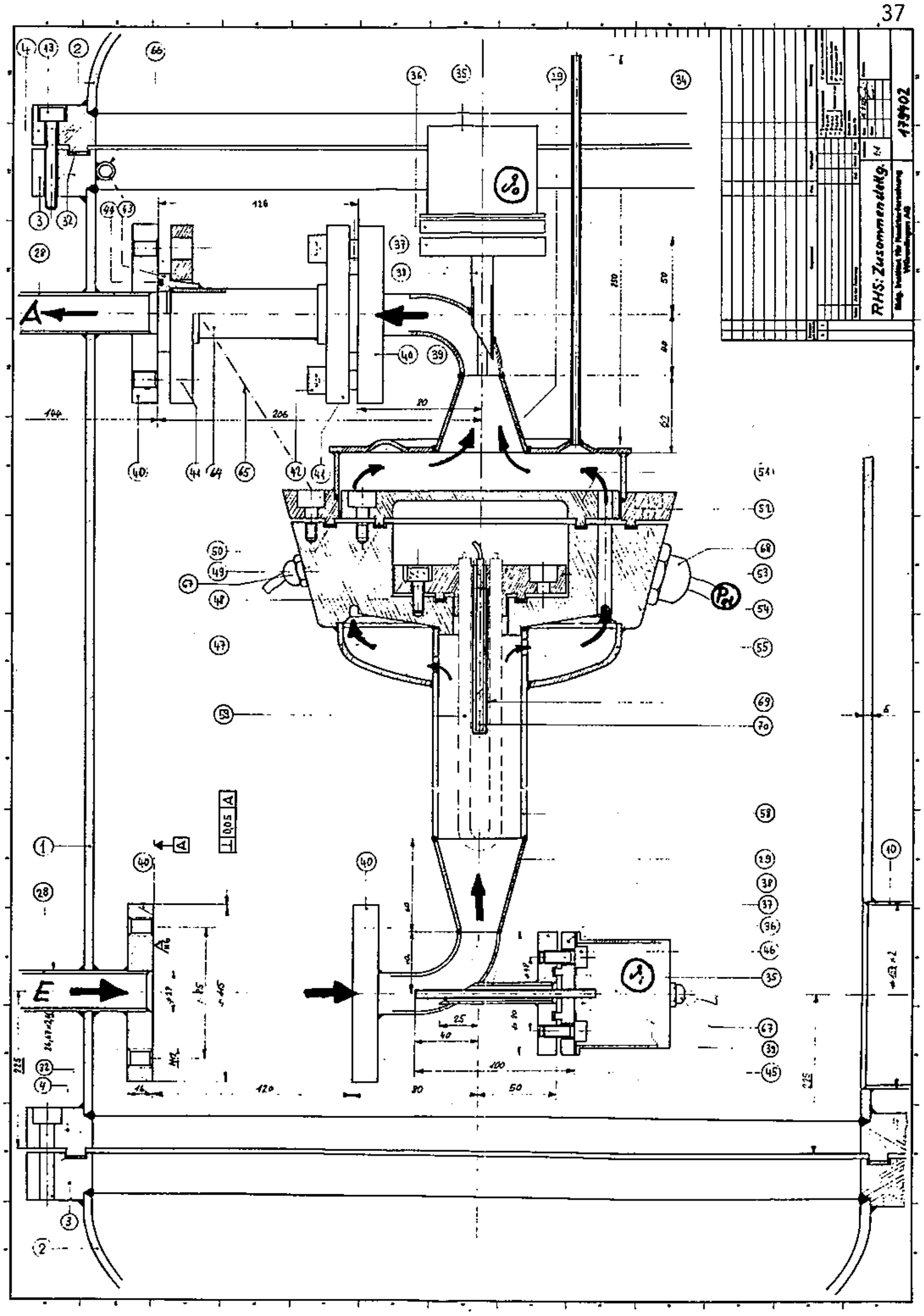

Fig 9. The RHS from Eidg. Institut für Reaktorforschung, Switzerland

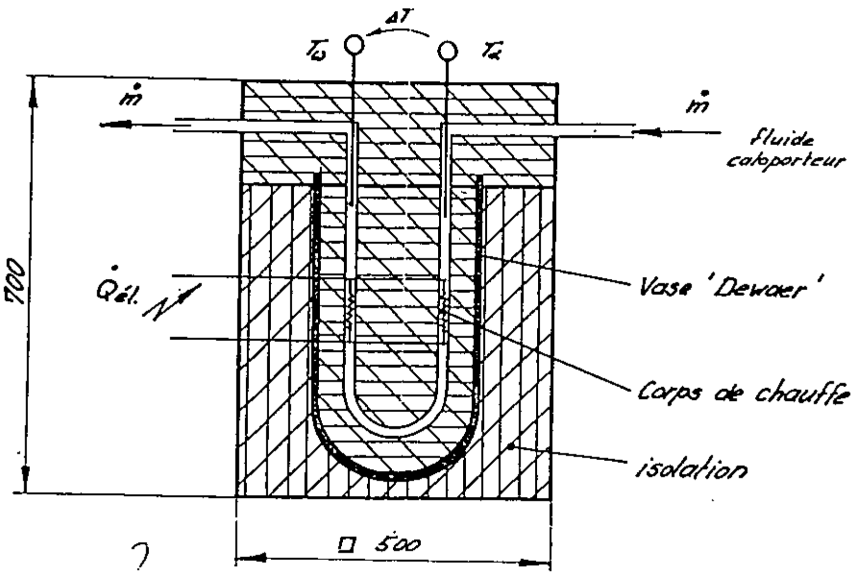

Fig 10. The RHS from EPFL, Lausanne, Switzerland

This report is part of the work of the IEA Solar Heating and Cooling Programme within

Task III:	Performance Testing of Solar Collectors,
Subtask A:	Development and Application of Standard Test Procedures for Determining Thermal Performance.

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