A Measurement Tool for Investigating Cooling Lava Properties

Bruno Andò, Mauro Coltelli, and Marilena Sambataro

***Abstract*—This paper presents the development and uncertainty characterization of a system for the direct measurement of heat transfer in cooling lava. The system continuously measures the parameters involved in the cooling process and, particularly, in the formation of the crust. The aim is to allow the future development of a physical model of the cooling process itself. In order to realize a system that will be effective in such a hostile environment, the principles on which the instruments for radiation thermometry are based have been thoroughly investigated. A virtual instrument has been developed, interfacing the measuring system and the user, processing the incoming data, and producing an estimate of the uncertainty of the measurement chain. The various sources of uncertainty have been taken into account to produce an accurate estimate of the uncertainty associated with the measured data. The results of experimental tests are presented.**

***Index Terms*—Cooling lava measurement, field point, radiation thermometry, whole system uncertainty estimate.**

I. Introduction

THE DEVELOPMENT of a physical model for cooling lava flows requires thorough knowledge of the heat transfer coefficient between hot lava and the cool surrounding environment. The heat exchange between lava and the atmosphere produces most of the crust, deeply modifying the rheological behavior of flowing lava.

In a previous work, some of the authors proposed a methodology for direct measurement of heat transfer in cooling lava [1]. It is based on the contemporaneous use of three different instruments to measure the temperature gradient in a lava flow close to the surface, and the temperature and thermal radiation of the lava-atmosphere interface.

The work presented in this paper is a realization and metrological characterization of a complete measurement system, in which the instruments are connected through a field point to a PC. The measured data is processed and stored by a virtual instrument developed in LabVIEW; the virtual instrument also represents a user interface to allow immediate visualization of the measured values. The measures obtained will give information about the evolution of both the temperature gradient of the cooling lava and the thermal emittance of the crust, allowing for characterization of the crust formation process.

The natural scenario in which the measurement task is to be performed is seriously hostile. Ground conditions and very high temperatures require a dedicated setup and reliable connections between the instruments and data processing device.

Moreover, risks for the user must be taken into account, and both easy-to-use interfaces and automatic measurement procedures are required.

On the basis of the above considerations, hard constraints are not required for this kind of measurement, especially as far as accuracy is concerned. However, the problem of formalizing a rigorous estimate of the system uncertainty has been dealt with by applying the law of uncertainty propagation, expressed in the ISO-Guide (GUM) [2], which establishes general rules for the estimation and expression in measurement uncertainty of the whole measurement chain. Since the publication of this guide, some applications of the GUM method have been proposed in literature for evaluating uncertainty in numerical algorithms or estimating the measurement uncertainty of a virtual instrument [3]. In this paper, we consider the whole measurement chain, taking into account all the possible sources of uncertainty and their propagation. An expression for uncertainty has been found, as well as a method for estimating uncertainty in complex systems.

A number of experimental tests were conducted, using an oven working at suitable temperatures to test the actual behavior of the whole system.

II. Overview of Radiation Thermometry

A wide class of instruments for radiation thermometry is based on thermal detectors [4], which experience a temperature change when they absorb infrared radiation. An electrical response results from the temperature difference between the detectors and their surroundings, depending on certain material properties. These detectors are usually thermally isolated from their surroundings to maximize the temperature change that results from the absorption of a small amount of infrared radiation.

This temperature measuring method is thus based on noncontact sensing, allowing the thermometer not to be brought into physical contact with the target.

This measuring method solves the problem of measuring temperature when the thermometer cannot withstand the temperature to be measured, or if the body whose temperature is to be measured is too far (stars), or if this body is moving.

A variety of instruments based on the sensing of radiation have been devised: radiometers, pyrometers, etc. Radiation-temperature sensors operate with electromagnetic radiation whose wavelengths lie in the visible and infrared portions of the spectrum, from 0.3 to 1000 μm.

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Every body above absolute zero in temperature emits radiation dependent on its temperature. The ideal thermal radiator is called a *blackbody*, and it emits the maximum amount of radiation possible.

The law governing ideal thermal radiation is Planck's law, which states that [4], [5]

$$W_\lambda = \frac{C_1}{\lambda^5 \left(e^{C_2/\lambda T} - 1\right)} \tag{1}$$

where

- $W\lambda$ hemispherical spectral radiant intensity $[W\text{cm}^{-2}\mu\text{m}^{-1}]$;
- C_1 37.413 $[W.\mu\text{m}^4\text{cm}^{-2}]$;
- C_2 14.388 $[\mu\text{m} \cdot \text{K}]$;
- λ radiation wavelength $[\mu\text{m}]$;
- T blackbody absolute temperature [K].

The total amount of radiation emitted at all wavelengths is obtained by integrating (1) [4]

$$W_t = 5.67 \cdot 10^{-12} T^4 \ [\text{W/cm}^2]. \tag{2}$$

The behavior of real bodies can be expressed in terms of deviation from blackbody radiation, defining the spectral emittance as

$$\varepsilon_{\lambda,T} = \frac{W_{\lambda a}}{W_\lambda} \tag{3}$$

where $W_{\lambda a}$ is the *actual* hemispherical spectral radiant intensity.

With the above definition, Planck's law for a real body becomes

$$W_{\lambda a} = \frac{C_1 \varepsilon_{\lambda,T}}{\lambda^5 \left(e^{(C_2/\lambda T)} - 1\right)} \tag{4}$$

while (2) becomes

$$W_{\text{ta}} = 5.67 \cdot 10^{-12} \varepsilon_{t,T} T^4 \ [\text{W/cm}^2] \tag{5}$$

where $\varepsilon_{t,T}$ is the hemispherical total emittance, defined as

$$\varepsilon_{t,T} = \frac{W_{\text{ta}}}{W_t}. \tag{6}$$

A body that has $\varepsilon_{\lambda,T}$ equal to a constant for all λ and at a given T is called a *graybody*, and $\varepsilon_{t,T} = \varepsilon_{\lambda,T}$.

If a radiation thermometer measuring the total incoming radiation W_{ta} has been calibrated against a blackbody source, knowledge of the appropriate emittance value allows a correct temperature reading.

Emittance is a material property, depending on size, shape, surface roughness and angle of viewing and can be used to study the structural evolution of the material analyzed during the observation process. If the target undergoes state changes, as in the case of the crust during the cooling lava process, its emittance varies accordingly. In these cases, accurate knowledge of W_{ta} and T leads, according to (5), to accurate knowledge of $\varepsilon_{t,T}$.

In fact, (5) can be written as

$$\varepsilon_{t,T} = \frac{1}{5.67 \cdot 10^{-12}} \cdot \frac{W_{\text{ta}}}{T^4}. \tag{7}$$

The target of the developed system is to give information on the emittance evolution by measuring the quantities W_{ta} and T.

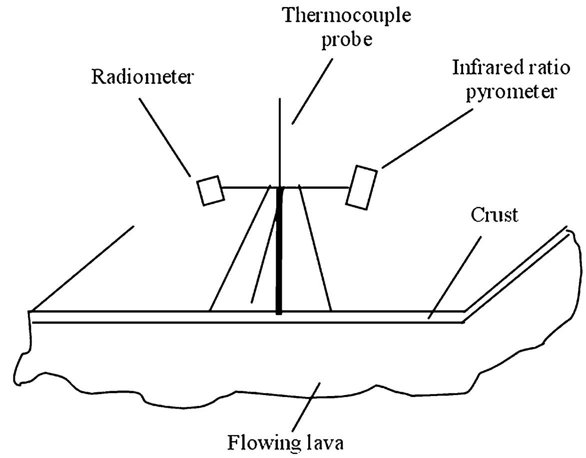

Fig. 1. Dedicated equipment has been developed allowing for a suitable measurement setup.

III. Measurement System

The experiment proposed in this paper simultaneously measures the two main components of the cooling process: conductive and radiant heat transfers. The apparatus consists of

a) five Pt-Pt10%Rh (S type) thermocouples in series to establish a very accurate gradient of temperature inside the lava flow;

b) a radiation thermopile to measure the heat flux to the atmosphere;

c) an infrared ratio pyrometer to measure the lava surface temperature.

The experimental setup is sketched in Fig. 1. The use of a high temperature resistant alloy structure allows good mechanical features to be achieved for the developed setup. Moreover, the instruments and data processing device are connected by shielded cables which perform well even in the presence of serious exogenous influences.

The lava temperature gradients will be measured close to the surface using five regularly spaced S-type (pt-Pt10%Rh) thermocouple hot junctions in series. The wires are housed in an alumina six-bore tube which will work inside a disposable Inconel sheath so as to be molten-lava resistant [4].

A temperature accuracy in the range of 0.5–1 °C is expected, taking advantage of the special thermocouple wires attached to the field point.

The radiometer is a heat flux sensor working on the principle that the difference in temperature across the thermal barrier is proportional to the heat flow through itself. The transducer is isolated from the atmosphere by an infrared filter and is focused on the target by collimating windows.

For a given source temperature T, the incoming radiation heats the measuring junction until conduction, convection and radiation losses just balance the heat input. An oversimplified analysis gives [4] heat loss = radiant heat input

$$(T_1 - T_2) \propto W_{\text{in}} \propto T^4 \tag{8}$$

where T_1 is the measuring junction temperature, and T_2 is the surrounding temperature.

While this instrument is very accurate for measuring radiant intensities, it is not very accurate for measuring temperatures.

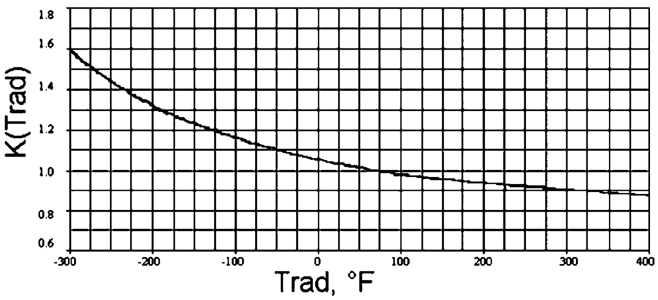

Fig. 2. Radiometer correction factor given by the producer. The implementation law suggested for it is $K(T_{\rm rad}) = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4$ with $a_0 = 1.055\,414\,995\,819\,44$, $a_1 = -0.000\,803\,082\,818\,42$, $a_2 = 0.000\,001\,646\,527\,11$, $a_3 = -0.000\,000\,003\,712\,74$, $a_4 = 0.000\,000\,000\,004\,32$.

The relationship between radiant intensity and temperature is given by (5) and shows that for an accurate knowledge of the surface temperature we need to know the surface emittance with good confidence.

The instrument response can be expressed in the form

$$W = K(T_{\rm rad}) \cdot k_1 \cdot V_{W,{\rm acq}} \left[\frac{W}{{\rm cm}^2}\right] \tag{9}$$

in which k_1 is a transduction constant given by the producer, and $V_{W,{\rm acq}}$ is the K-type thermopile voltage output.

$K(T_{\rm rad})$ is a correction factor which depends upon the internal temperature $T_{\rm rad}$, measured by the K-type thermocouple, as shown in Fig. 2.

An accurate temperature measure is obtained by using a two-color radiation pyrometer [4]–[6]. This instrument measures the spectral radiant intensity for two different wavelengths, and then the ratio of these two W_λ is taken as a measure of temperature. If W_λ is expressed by (4), the measured ratio is

$$\frac{W_{\lambda_1}}{W_{\lambda_2}} = \frac{\varepsilon_{\lambda_1,T}}{\varepsilon_{\lambda_2,T}} \cdot \left(\frac{\lambda_2}{\lambda_1}\right)^5 e^{C_2/T \cdot ((1/\lambda_2)-(1/\lambda_1))} \tag{10}$$

which for a graybody becomes

$$\frac{W_{\lambda_1}}{W_{\lambda_2}} = \left(\frac{\lambda_2}{\lambda_1}\right)^5 e^{C_2/T \cdot ((1/\lambda_2)-(1/\lambda_1))}. \tag{11}$$

If the chosen wavelengths are close enough, (11) represents a good approximation even for actual bodies. This allows great accuracy in temperature measurement even in conditions of unknown or changing emittance.

The measured temperature is a function of the voltage response of the pyrometer in a way that depends upon its calibration. In our case

$$T \approx 500 V_{T,{\rm acq}}. \tag{12}$$

This instrument has a reading accuracy of 0.5%.

Due to the hostile environment which is the natural scenario of the measurements performed, a suitable setup is required to assure reliability. On the basis of this consideration, a field point architecture was adopted, connected to the measuring devices by shielded cables. The latter perform well even in the presence of serious exogenous influences.

Moreover, the need to avoid risks for the user requires an automatically running measurement system with an easy-to-use user interface. A laptop is used to manage the measurement session, connected to the field point system to collect and process the data acquired.

TABLE I
FIELD POINT SPECIFICATIONS

Number of channels	8	
ADC resolution	16 bits	
Conversion	Delta-Sigma	
Gain error (a_G)	(25°C) (-40 to 70°C)	0.01% typ., 0.03%max. 0.046% typ., 0.12%max.
Offset error (a_{OFF}) (15° to 35°C)	Input range: ± 25 mV ± 50 mV ±100 mV -20 to +80 mV	 3 μV typ., 5 μVmax. 3.5 μV typ., 6 μVmax. 4 μV typ., 7 μVmax. 3.5 μV typ., 8 μVmax.
Offset error (-40° to 70°C)	Input range: ± 25 mV ± 50 mV ±100 mV -20 to +80 mV	 4.5 μV typ., 13 μVmax. 5 μV typ., 13 μVmax. 5.5 μV typ., 15 μVmax. 5 μV typ., 13 μVmax.
Input noise (a)	±1 LSB	

All the instruments are connected to the field point, which acquires both signals from thermocouples and radiation instrument outputs. The field point comprises the modules FP-1000 (RS-232 Network Module) and FP-TC-120 (8-Channel Thermocouple Input Module). Its specifications, as regards voltage acquisition, are shown in Table I.

As regards temperature acquisition, this module uses a linearization algorithm (according to the NIST-175 standard for thermocouples of the National Institute of Standards and Technology, based on the international temperature scale ITS-90), and measures temperatures with an accuracy of ±0.05 °C (±0.03 °F) over the entire temperature range.

IV. Virtual Instrument

In order to provide an easy-to-use interface and to implement the algorithm for emittance estimation, a virtual instrument has been developed in LabVIEW. The instrument manages the acquisition process by controlling the field point system, which collects data from the radiation instruments and the thermal probe. The field point is periodically queried by the software tool in order to acquire data, which is stored in user-defined files. At the same time, suitable data processing is performed to provide the user with both the real-time values of the required parameters (emittance, temperature gradients, and thermal radiation) and estimation of the uncertainty of the measurement process.

Fig. 3 shows the front panel as seen by the user. As can be observed, each section of the interface is dedicated to a well-defined task: setting values and the distance between the instruments and the surface, setting the parameters for data recording, showing the instantaneous value of the data measured, giving information on the uncertainty associated with the measured values, and plotting the evolution of both the data acquired and the estimated emittance.

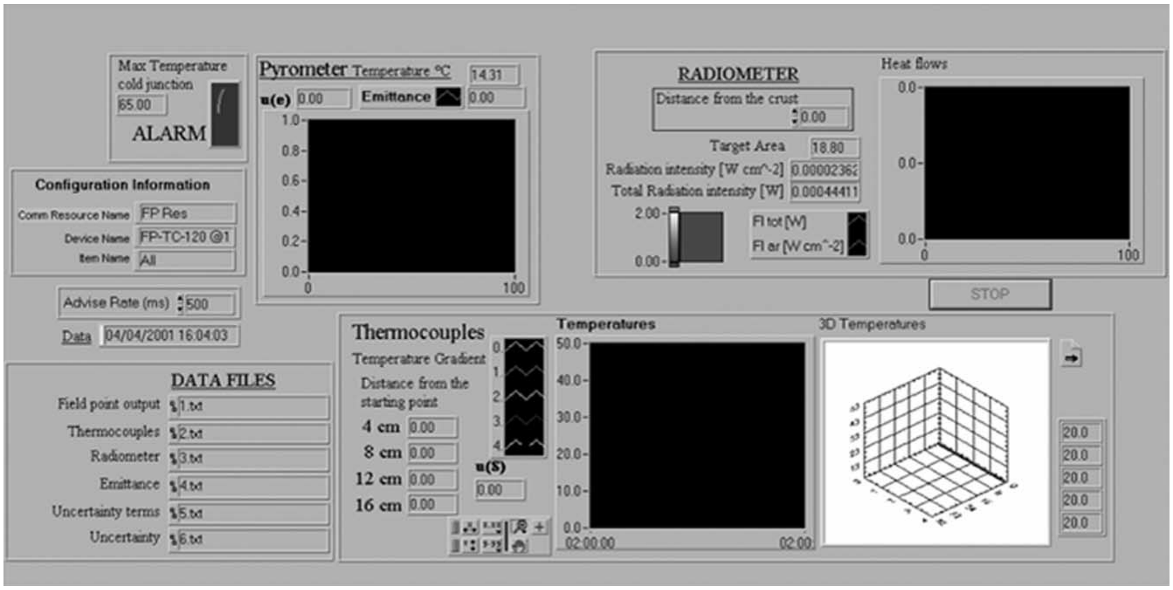

Fig. 3. Front panel of the virtual instrument for monitoring the evolution of the lava cooling process.

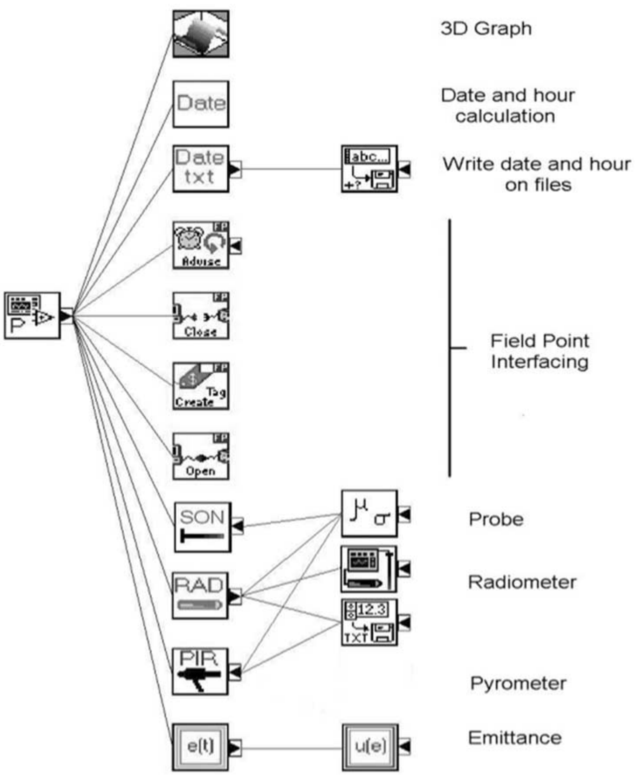

Fig. 4. Hierarchy of the developed instrument. From the top: the three-dimensional graph VI manages temperature plot; date VI records acquisition time; field point VIs manages data gathered by field point; SON, RAD, and PIR VIs elaborate data coming from the temperature probe, radiometer, and pyrometer, respectively; $e(t)$ and $u(e)$ VIs estimate emittance evolution and uncertainty respectively.

The virtual instrument is made up of a number of subVIs, as can be seen in Fig. 4, which shows the program hierarchy. The whole measurement procedure is sketched in Fig. 5, which illustrates the activities of each subVi and the data flow leading to emittance estimation and uncertainty calculation.

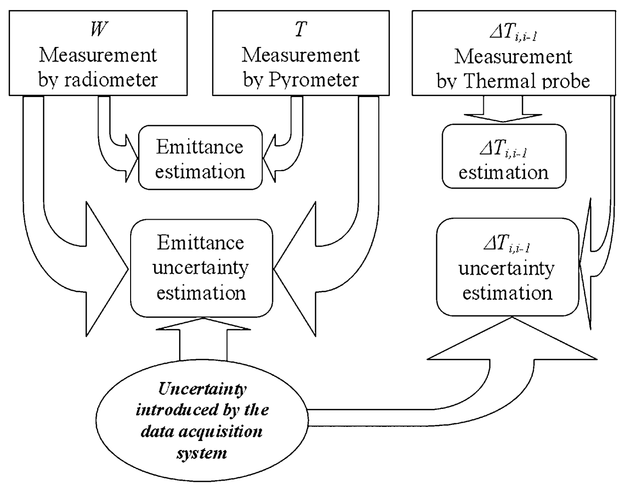

Fig. 5. Activities performed by the LabVIEW tool managing the measurement session.

A number of subVIs are used to communicate with the field point, while others calculate the temperature gradients on the surface. The "pyrometer" subVI calculates the surface temperature according to (12) and sends the data to files and to the "mean and variance" subVI. The "radiometer" subVI implements the radiometer conversion law, expressed by (9), calculating the radiant flux emitted by the surface. The "radiometer" subVI also checks the field point temperature, which should not exceed 70 °C to avoid wrong behavior or damage to the field point itself.

All the acquired data is stored and sent to a subVI, which calculates the mean value and variance of a certain amount of data, chosen by the user according to the time constants of the process.

The "emittance" subVI calculates emittance using the surface temperature and the radiant flux coming from the "pyrometer" and "radiometer" subVIs, implementing (7). The "uncertainty" subVI estimates the uncertainty associated with the emittance value according to the method outlined in Section V.

V. Uncertainty Estimation

According to [2], the combined standard uncertainty estimate $u_c(y)$ of a quantity y, which has been determined from N other quantities $x_1, x_2, \ldots x_N$ through a functional relation $y = f(x_1, x_2, \ldots x_N)$ is the positive square root of the estimate variance $u_c^2(y)$, obtained from the law of uncertainty propagation

$$u_c^2(y) = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i}\right)^2 \cdot u_c^2(x_i) + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N} \frac{\partial f}{\partial x_i} \cdot \frac{\partial f}{\partial x_j} \cdot u(x_i, x_j) \quad (13)$$

where $u_c(x_i)$ is the estimated standard uncertainty associated with the input estimate x_i, and $u(x_i, x_j)$ is the estimated co-variance associated with x_i and x_j. This equation is based on a first-order Taylor series approximation of y.

The measurement system to be analyzed is made up of different blocks contributing to the measurement uncertainty:

a) two radiation thermometers and a thermocouple probe;
b) a field point for signal acquisition;
c) a PC;
d) LabView software (control, data processing, analysis, presentation, interfacing, etc.).

The quantities to be measured by the system are the surface emittance and the temperature gradients close to the surface.

The surface emittance is calculated using (7) where the symbol W is used instead of W_{ta} for the sake of simplicity

$$\varepsilon_{t,T} = \frac{1}{5.67 \cdot 10^{-12}} \cdot \frac{W}{T^4}. \quad (14)$$

Using the law of uncertainty propagation, and considering W and T to be uncorrelated, the estimate variance can be expressed as follows:

$$u^2(\varepsilon_{t,T}) = \left(\frac{\partial \varepsilon_{t,T}}{\partial T}\right)^2 \cdot u^2(T) + \left(\frac{\partial \varepsilon_{t,T}}{\partial W}\right)^2 \cdot u^2(W). \quad (15)$$

Let us first consider the term due to the temperature estimate given by the pyrometer.

The measured temperature depends on the output voltage

$$T = f_T(V_{T,\text{acq}}) \quad (16)$$

and then

$$u^2(T) = \left(\frac{\partial f_T}{\partial V_{T,\text{acq}}}\right)^2 \cdot u^2(V_{T,\text{acq}}). \quad (17)$$

In order to calculate the global uncertainty on voltage acquisition it is possible to sum the estimate variances of the various sources of uncertainty, obtaining

$$u^2(V_{T,\text{acq}}) = u_1^2(V_{T,\text{acq}}) + u_2^2(V_{T,\text{acq}}). \quad (18)$$

The first term is due to instrument uncertainty, and its estimate variance is

$$u_1^2(V_{T,\text{acq}}) = \frac{a_V^2}{3}$$

where a_V is the half width of the value distribution interval, given by the producer.

The second term in (18) is due to the acquisition process.

As far as voltage acquisition is concerned, there are different sources of uncertainty:

a) gain errors;
b) offset errors;
c) quantization errors;
d) noise errors;
e) finite microprocessor word length;
f) time jitter errors.

The last two terms may be considered negligible, so the total estimate variance is given by the sum of the variances of the different sources of uncertainty

$$u_2^2(V_{T,\text{acq}}) = u^2(\text{Gain}) + u^2(\text{Offset}) + u^2(\text{Quant}) + u^2(\text{Noise}) \quad (19)$$

where

$$u^2(\text{Gain}) = a_G^{2/3}$$
$$u^2(\text{Offset}) = a_{\text{OFF}}^{2/3}$$
$$u^2(\text{Noise}) = a^{2/3}$$

and

$$u^2(\text{Quant}) = \frac{(A \cdot 2^{-16})^2}{12}$$

A being the half width of the voltage amplitude interval and $A/2^{16}$ the quantization step.

Let us now calculate the second term in (15), due to radiometer errors.

Again, using the law of uncertainty propagation for (9), we obtain

$$u^2(W) = \left(\frac{\partial W}{\partial T_{\text{rad}}}\right)^2 \cdot u^2(T_{\text{rad}}) + \left(\frac{\partial W}{\partial V_{W,\text{acq}}}\right)^2 \cdot u^2(V_{W,\text{acq}}). \quad (20)$$

As T_{rad} is a K-thermocouple-measured temperature, its uncertainty is given by the thermocouple accuracy a_K,and the linearization algorithm used by the field point, whose accuracy a_{FP} is given in the field point specifications. It is possible to sum the two uncertainty variances, obtaining

$$u^2(T_{\text{rad}}) = u_1^2(T_{\text{rad}}) + u_2^2(T_{\text{rad}}) \quad (21)$$

with

$$u_1^2(T_{\text{rad}}) = \frac{a_K^2}{3} \text{ and}$$
$$u_2^2(T_{\text{rad}}) = \frac{a_{FP}^2}{3}.$$

The estimated variance of $V_{W,\text{acq}}$ comprises two terms

$$u^2(V_{W,\text{acq}}) = u_1^2(V_{W,\text{acq}}) + u_2^2(V_{W,\text{acq}}) \quad (22)$$

and, again, the first is due to the accuracy of the instrument (a thermocouple), while the second is due to the acquisition process and is given by (19).

In regard to the first term, the estimate uncertainty variance can be calculated considering that the instrument response is a voltage corresponding to a measured temperature through a functional relation which is different for each thermocouple type

$$V = g(T) \tag{23}$$

then

$$u_1^2(V) = \left(\frac{\partial g}{\partial V}\right)^2 \cdot u^2(T) \tag{24}$$

where $u^2(T)$ is the variance of the thermocouple uncertainty. It is possible to simplify this equation using a first-order approximation of $g(T)$.

The second quantity measured by the thermocouple probe is the temperature gradient close to the surface. As for T_{rad}, the uncertainty in the temperature estimate is due to the S-thermocouple accuracy and to the linearization algorithm used by the field point

$$u^2(T_{\text{probe}}) = u_1^2(T_{\text{probe}}) + u_2^2(T_{\text{probe}}) \tag{25}$$

with

$$u_1^2(T_{\text{probe}}) = \frac{a_S^2}{3}$$
$$u_2^2(T_{\text{probe}}) = \frac{a_{FP}^2}{3}.$$

Considering a generic temperature gradient $\Delta T_{i,i-1} = T_i - T_{i-1}$, it follows that

$$u^2(\Delta T_{i,i-1}) = u^2(T_i) + u^2(T_{i-1}) = 2u^2(T_{\text{probe}}). \tag{26}$$

VI. Experimental Test

After the design and realization of the system, various tests were conducted in order to test the actual behavior of each instrument, the software and the whole measurement chain.

To simulate the lava flow a temperature-controlled oven was used, which can reach temperatures close to 1200 °C, i.e., the surface temperature of cooling lava. The experimental setup is shown in Fig. 6.

The test bed adopted allows us to verify the operational efficiency and performance of the developed tool in terms of ease of use, device connections, correctness of data processing, and capacity for real-time signal processing.

For example, during one of the tests conducted the following measures for W and T were given: $T = 1000$ °C and $W = 14.89\ W/\text{cm}^2$.

It should be noted that the emittance value is quite close to 1 due to the nature of the radiation source.

From (14)

$$\left(\frac{\partial \varepsilon_{t,T}}{\partial T}\right)^2 = \left(\frac{1}{5.67e-12} \cdot \frac{W}{T^5}\right)^2 = \left(\frac{14.89}{5.67e-12 * (1273)^5}\right)^2 = 0.62e^{-6\circ}\text{C}^{-2}$$

$$\left(\frac{\partial \varepsilon_{t,T}}{\partial W}\right)^2 = \left(\frac{1}{5.67e-12} \cdot \frac{1}{T^4}\right)^2 = \left(\frac{1}{5.67e-12 * (1273)^4}\right)^2 = 4.5e^{-3}\left(W^{-2}\text{cm}^4\right).$$

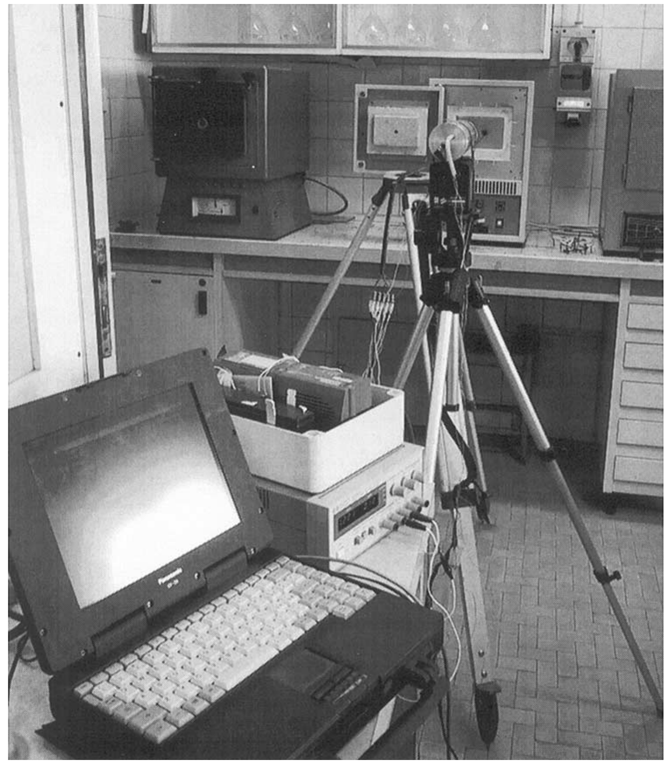

Fig. 6. Experimental setup.

As the pyrometer accuracy is 5 °C, from (12), it follows that $u_1(V) = 10$ mV, and using the parameters in Table I for a voltage input in a range of ±50 mV, (17) becomes

$$u^2(T) = (500)^2(u_1^2(V) + u_2^2(V) = 8.37(\ ^\circ\text{C}^2).$$

Using a linear approximation for $K(T_{\text{rad}})$, with $T_{\text{rad}} = 21$ °C, from (9), it follows that

$$\left(\frac{\partial W}{\partial V_{W,\text{acq}}}\right)^2 = [K(T_{\text{rad}}) \cdot k_1]^2 = 4.49\left(W^2\text{cm}^{-4}\text{V}^{-2}\right)$$
$$\left(\frac{\partial W}{\partial T_{\text{rad}}}\right)^2 = [a_2 \cdot k_1 \cdot V_{\text{acq}}]^2 = 11.9e^{-3}\left(W^2\text{cm}^{-2\circ}\text{C}^2\right)$$

$u^2(T_{\text{rad}})$ is due to the k-thermocouple accuracy (0.7 °C) and to the accuracy of the linearization algorithm used by the field point (0.05 °C); from (21)

$$u^2(T_{\text{rad}}) = 0.49\ (^\circ\text{C}^2).$$

By considering an approximate conversion law for K-type thermocouples and (24), it follows that

$$u_1^2(V) = 0.274e^{-9}\ (\text{V}^2)$$

and since $u_2^2(V) = 182e^{-9}$ (V^2), from (22) it follows that

$$u^2(V) = 182e^{-9}\ (\text{V}^2).$$

Substituting in (20), we get

$$u^2(W) = 4.37\ (W^2\text{cm}^{-4}).$$

Combining the previous results, it follows that

$$u(\varepsilon_{t,T}) = 0.14.$$

As far as the uncertainty for the temperature gradient is concerned, a first source of uncertainty is due to the S-thermocouple accuracy (± 1 °C) and a second one to the field point linearization algorithm (± 0.05 °C). Using (25) yelds $u^2(T) = 0.334\,°\mathrm{C}^2$ and from (26)

$$u(\Delta T) = 0.812\ °\mathrm{C}.$$

The uncertainty values obtained fit the required features of the developed system. It should be noted that for this kind of measure, accuracy cannot be assured due to the hostile working environment. However, the authors are quite confident in the capability of the developed setup to fit the required performance also during real operations.

VII. Conclusion

The system developed is of great interest for the geophysical characterization of lava flow and crust formation, and it represents an efficient method for a rough analysis of the process of evolution leading to the rheological classification of flowing magma. The easy-to-use interface and the automatic mode running the measurement procedure represent important features of the system.

Results obtained during the test phase revealed suitable performances of the system developed; the estimated uncertainty both for temperature and emittance measurements fits the required limits. The system performances during real operations could be influenced from environmental conditions. The setup reliability encourages its use for real experiments also in hostile working environments; and real experiments will be performed, in the near future, to test the system features.

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