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Research Article

Basics of Air-Flow Calorimetry

Jacques Ruer*

SFSNMC, France

Abstract

In the Mass Flow Calorimetry method, the heat released by an LENR reactor under test is measured by monitoring the temperature increase of a known flow of fluid passing over it. In the Air Flow Calorimetry method (AFC), the fluid is air. AFC appears to be a relatively simple method to measure the amount of heat produced by an LENR reactor. It is well suited when the LENR reactor surface temperature is high. It is easier to build than mass flow calorimeters using water-cooled or oil-cooled systems. Basically, the calorimeter is designed such that all the heat produced by the device under test is transferred to a known mass flow of cooling air. The accuracy of the method is governed by the control of the heat losses, the mass flow-rate of cooling air, the air heat capacity, the measure of the average air temperatures at inlet and outlet. Transpiration cooling is an efficient design to minimize the heat losses. The AFC method can be applied to reactors of any size and surface temperature. Its use is restricted to the testing of reactors that work continuously, because thermal equilibrium must be reached to make valid measurements. A thorough calibration procedure is essential to minimize the influence of errors on mass flows and temperature differences.

Keywords: Air flow calorimetry, Air heat capacity, Calibration, Flow meters, Heat measurement, High temperature, Transpiration cooling

1. Introduction

In the Mass Flow Calorimetry method, the heat released by a hot object is measured by monitoring the temperature increase of a known flow of fluid passing over it [1].

In the Air Flow Calorimetry method (AFC) the fluid is air. AFC appears to be a relatively simple method to measure the amount of heat produced by an LENR reactor. A recent example of the method was presented by Mizuno [2]. It is well suited when the LENR reactor surface temperature is high. It is easier to build than mass flow calorimeters using water-cooled or oil-cooled systems [1–3]

Basically, the calorimeter is designed such that all the heat produced by the device under test is transferred to a known mass flow of cooling air. According to the first principle of thermodynamics the rise of temperature of the air flow between the inlet and the outlet of the calorimeter is linked to the heat input by Eq. (1).

$$Q = C_{\mathrm{p\,m}}\,(T_{\mathrm{out}} - T_{\mathrm{in}}) + \mathrm{Losses}, \quad (1)$$

*E-mail: jsr.ruer@orange.fr.

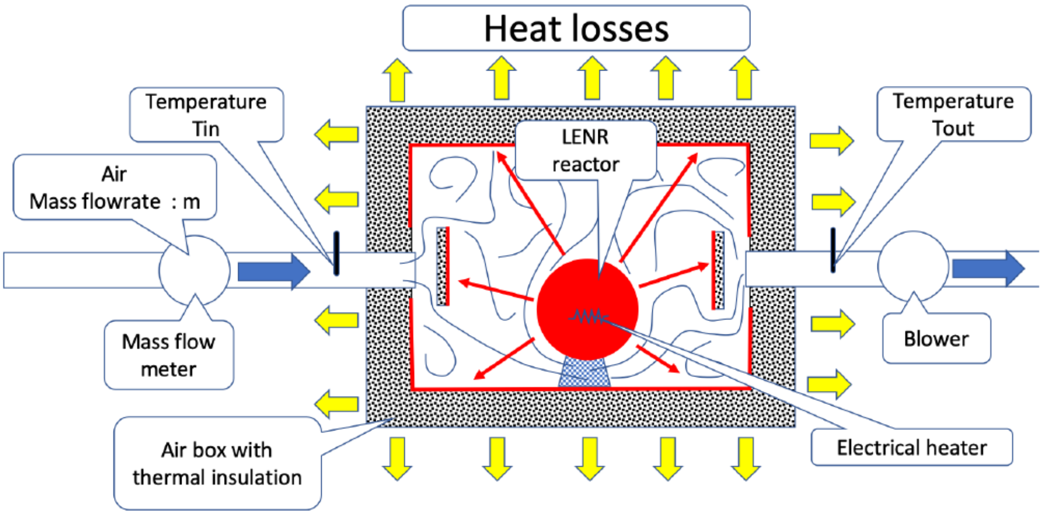


Figure 1. Sketch showing the main AFC features. The reactor tested is placed in an enclosed insulated box. A flow of air exports the heat released. Some heat is lost through the walls because the insulation is not perfect.

Q is the heat power (W), C_p the air heat capacity (J kg $^{-1}$K^{-1}), m the air mass flow rate (kg s^{-1}).

The AFC box that contains the reactor cannot be perfectly insulated. The losses must be taken into account. The method is well suited for stable continuous processes operated during periods much longer than the transient temperature evolution during the start-up phase. By nature, AFC is not applicable for the study of short-lived phenomena. For a discussion of this see also [1].

Transients may be analyzed by the technique developed by Higgins and Letts [4], but this is beyond the scope of this paper. In the following it is supposed that the heat flow is constant and that all measurements are taken when equilibrium conditions are reached.

Although the basic principle is simple, the accuracy of the method is influenced by many factors. We will show that AFC is able to deliver meaningful results with a careful calibration. This paper is an overview of the main parameters involved in air flow calorimetry, the possible problems that may affect the accuracy and the potential solutions to solve these problems.

2. Review of AFC Parameters

Figure 1 is a schematic view of an AFC system. AFC is governed by the following parameters:

- Air mass inlet and outlet – influence of enclosure leaks.
- Air heat capacity.
- Air temperatures at inlet and outlet.
- Heat losses: the insulation of the enclosure is not perfect.

These different factors are detailed later. But it is first necessary to examine how the heat released by the reactor is

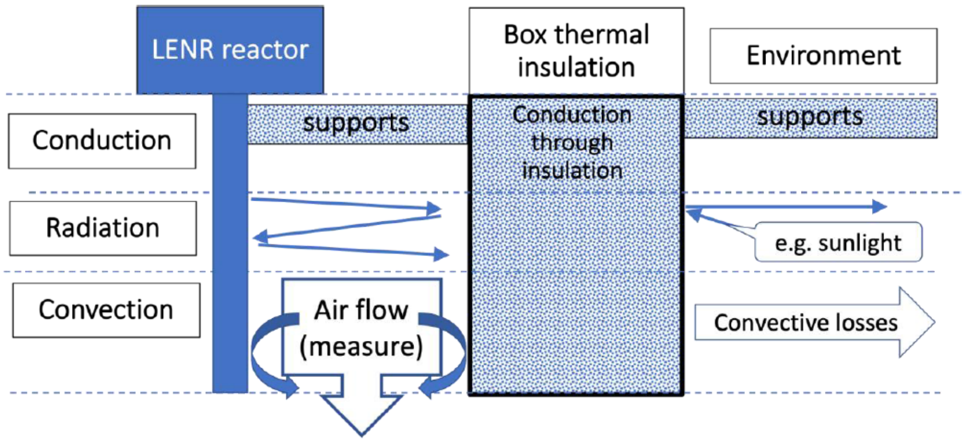


Figure 2. Heat transfer phenomena in AFC.

transferred to the flow of cooling air.

2.1. Transfer of heat between the hot device and air in AFC

How the heat is transferred from the hot LENR device to the air must be considered in detail. The different heat transfer mechanisms are summarized in Fig. 2. Conduction, radiation and convection must be taken into account.

- *Conduction*: Heat is conducted through the wall insulation and the mechanical supports that hold the LENR device in place. Insulation and supports must be designed to minimize the heat lost by conduction to the environment.
- *Radiation*: Air is transparent to infrared, at least if the dimensions of the enclosure are small enough to neglect the absorption by the tiny amounts of H_2O and CO_2 in the atmosphere. All the heat radiated by the reactor hits the walls. If the walls are coated by a reflective surface the infrared photons bounce several times between the solid surfaces contained in the box. Finally, all photons are absorbed by the solids. Heat is then transferred to the air by convection, unless it escapes to the environment via conduction through the box thermal insulation.
- Because the surface area of the walls is much larger than the reactor surface area the largest share of the infrared heat is exchanged to the air by the walls. The heat lost across the thermal insulation is evacuated to the environment by convection in free air and also by radiation. The room environment influences these exchanges. If a stream of air or if sunlight hit the box the thermal behavior is altered. Precautions should be taken to avoid a direct exposure of the box to uncontrolled air flows or the sun at any time of the day
- Radiation from the reactor can affect the sensors that monitor the air flow temperature if they are in direct view of the reactor, especially if the LENR reactor is very hot. To avoid this disturbance a screen should be arranged to block the direct view.
- *Convection*: Inside the box convection is the only useful heat transfer mechanism as far as AFC is considered. The surface area and the heat exchange coefficients between the reactor and the cooling air and between the walls and the air have an influence on the equilibrium surface temperature of the reactor and of the walls.

3. Influence of AFC size on Reactor Temperature

From this analysis we can conclude that the design of the AFC box has an influence on the relationship between the reactor power and its surface temperature.

Figure 3 shows an example. A simplified model calculates the behavior of an LENR reactor installed inside two different boxes with different wall areas. For a given heat power the reactor is hotter if it is located in the small box. Many authors report a correlation between the reactor temperature and its power. Therefore great care must be devoted to the analysis of measurements made by use of an AFC.

4. Influence of Heat Losses

Any heat that is not carried away by the cooling air flow is not measured directly. The calorimeter enclosure must be leak-free and a good thermal insulation is required to minimize the heat losses. The energy input of the air blower must be taken into account. An experimental discussion is provided in [2].

The heat lost through the walls depends on the insulation quality but also on the external conditions. The heat loss is governed by the surface area of the box walls and by the temperature difference between the inner face of the wall insulation and the environment. We have seen that the smaller the box, the higher the wall equilibrium temperature. The trade-off is not easy to find. We present a solution to this problem in the next section.

Other features of the calorimeter may have some impact on accuracy. For example, if the air inlet and air outlet are installed at different locations on the calorimeter enclosure the temperature distribution inside the air box is affected and heat losses are modified [56].

The hottest air tends to gather under the roof of the enclosure. It is therefore advisable to locate the air exit at the top in order to minimize the quantity of hot air accumulated in the box.

5. Transpiration Cooled Screen (TCS)

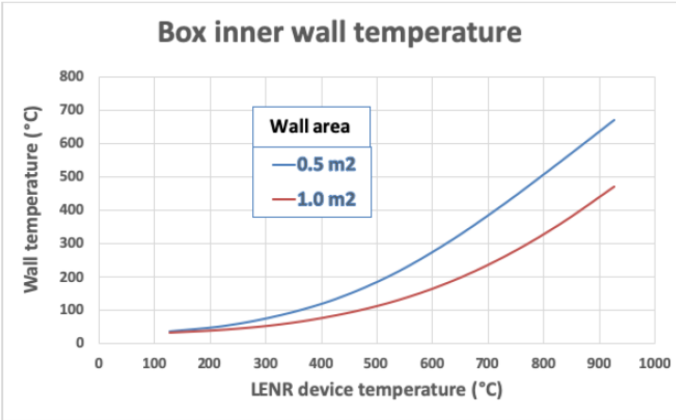
Transpiration cooling of a hot surface is caused by a flow of cool gas across the porous surface. Figure 4 shows for example the conceptual view of a gas turbine blade designed with transpiration cooling. Figure 5 shows a schematic view of an AFC system where the reactor is confined in an internal box made of Transpiration Cooled Screens (TCS). The cooling air percolates through the screens from the outside of the box to the internal volume. The air is pumped by a blower. With a proper design, all the heat received by the screens is transferred to the airflow.

Let us consider the heat flow on one of these screens (Fig. 6). On the inner face a given heating power is received (by example via radiation). The air flows through the screen with a space velocity V (assuming no solid in the screen). The screen thickness is L and the thermal conductivity of the screen material is λ. The screen material is ideally made of a porous material such as a layer of ceramic fibers. A numerical model has been written to simulate this. It uses an iterative method to calculate the temperature distribution of the solid and the air within the TCS. The calculation requires the introduction of the heat capacity of the solid to solve the transient evolution of the temperatures. However, the heat capacity has no influence on the temperature distribution at equilibrium.

The model shows that the behavior of the TCS depends on the value of the ratio F:

$$F = \frac{\lambda}{L\rho C_p V} \tag{2}$$

F represents the ratio of the heat transported by the conduction in the solid and the heat transported in the reverse direction by the air flowing through the screen. Figures 7 and 8 present typical results. In Fig 7, the screen is made of a heat conductive metal (steel wool). The F factor is larger than 1. There is a large temperature gradient on the outer face of the screen, indicating that heat is lost to the environment. Such a TCS is inefficient.



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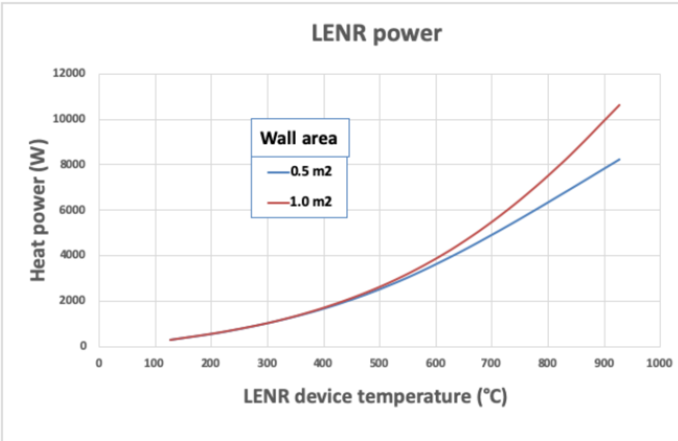

(**b**)

Figure 3. Example of the interaction between the reactor and airflow calorimeters of different sizes. Model hypotheses: The insulation of the box is perfect. All the heat radiated by the reactor is absorbed by the box wall and exchanged to the cooling air. Convection exchange coefficient: 20 $\mathrm{W\,m^{-2}\,K^{-1}}$ on all surfaces , emissivity is 0.8, LENR reactor surface area 0.1 m^2 , blue curves, box surface area 0.5 m^2 , red curves, box surface area 1.0 m^2 the size of the box has an effect on the reactor surface temperature at a given power level. (a) Relationship between the temperature on the reactor surface and the box inner wall temperature. (b) Relationship between the reactor power and its surface temperature.

On the other hand, Fig. 8 shows the temperature distribution calculated in a screen made of an insulating fiber mat. The temperature gradient on the outer face is negligible. All the heat is recovered by the cooling air. There is basically no heat loss to the environment.

Transpiration cooling is therefore a very efficient arrangement to eliminate the heat losses in AFC. It eliminates the interference between the AFC size and the reactor temperature because the TCS inner surface is kept at a moderate temperature level, close to the air outlet temperature.

6. Testing High Temperature Reactors

Some reactors are operated at a high temperature, well in excess of 300°C. AFC can be applied with the setup configuration shown in Fig. 9. The reactor is wrapped with an insulation mantle that creates a temperature drop between the reactor itself and the external surface of the mantle. The insulation thickness must be selected in order to obtain the desired operational characteristics. The mantle temperature governs the heat transfer while its thickness dictates the reactor temperature. Test of several mantles with increasing thicknesses may be required to find the correct balance of temperatures. The advantage of AFC is the absence of water or flammable oil that may cause some problems in case of leakage. Again, such an AFC experiment is only feasible if the reactor generates heat in a reproducible continuous and stable fashion.

7. AFC Measurements

7.1. AFC parameters

As mentioned earlier AFC requires the measurements of the following parameters:

- Air mass inlet and outlet.
- Air heat capacity.
- Air temperatures at inlet and outlet.
- Heat losses: the insulation of the enclosure is not perfect.

Any error on these parameters has an influence on the AFC accuracy. The influence of the different sources of error is discussed below.

7.2. Air mass flow rate and heat capacity

The cooling capacity of the air flow depends on the product mC_p
The mass flow is measured by appropriate sensors located in the air inlet or outlet pipe. If the pipe section area is S

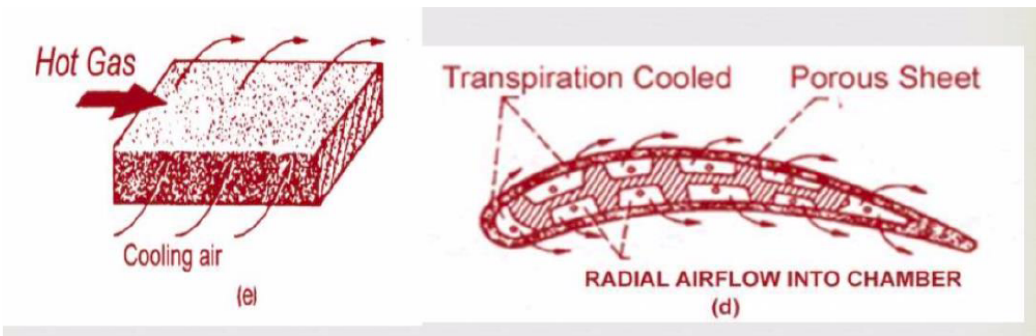

Figure 4. Conceptual view of transpiration cooling applied to gas turbine bladessource [7].

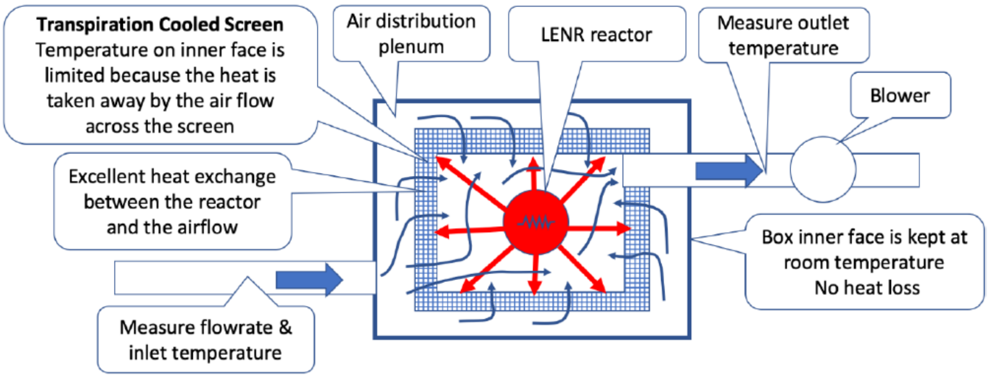

Figure 5. Schematic view of an AFC equipped with a transpiration cooled enclosure.

the mass flow is

$$mC_\mathrm{p} = \rho S V C_\mathrm{p}. \tag{3}$$

- ρ ($\mathrm{kg\,m^{-3}}$) is the air density that depends on the local atmospheric pressure, room temperature and relative humidity.
- V ($\mathrm{m\,s^{-1}}$) is the average velocity in the pipe. Most sensors give the air velocity at one point (e.g. on pipe

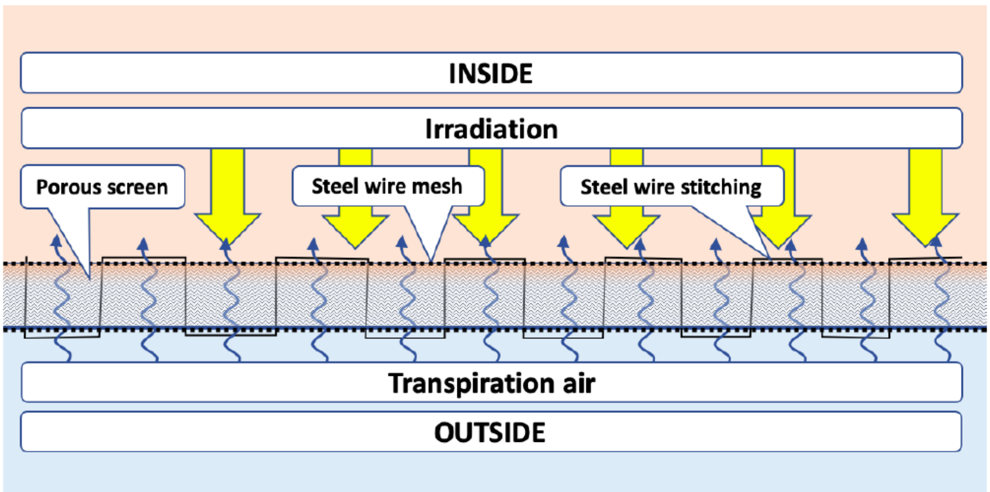

Figure 6. Sketch of a transpiration cooled screen.

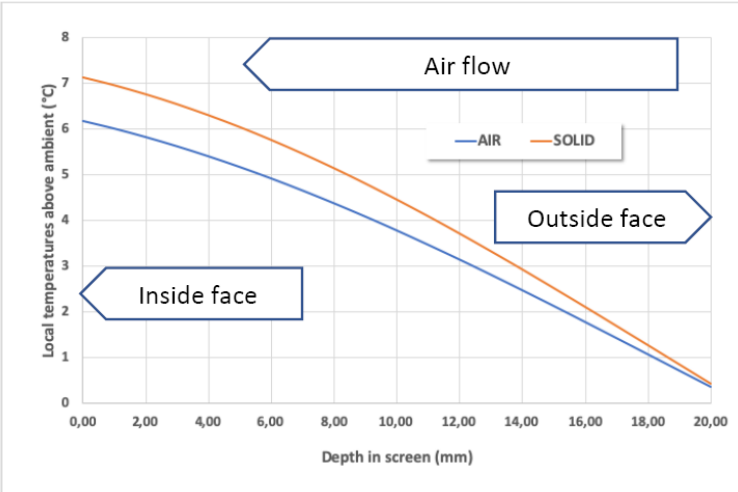

Figure 7. Temperature distribution in a TCS made of steel wool Irradiation: 1000 W m^2, $\lambda = 6.7\ \mathrm{W\,m^{-1}\,K^{-1}}$, $V = 0.05\ \mathrm{m\,s^{-1}}$, and $F = 5.3$, note the temperature gradient on the outer face.

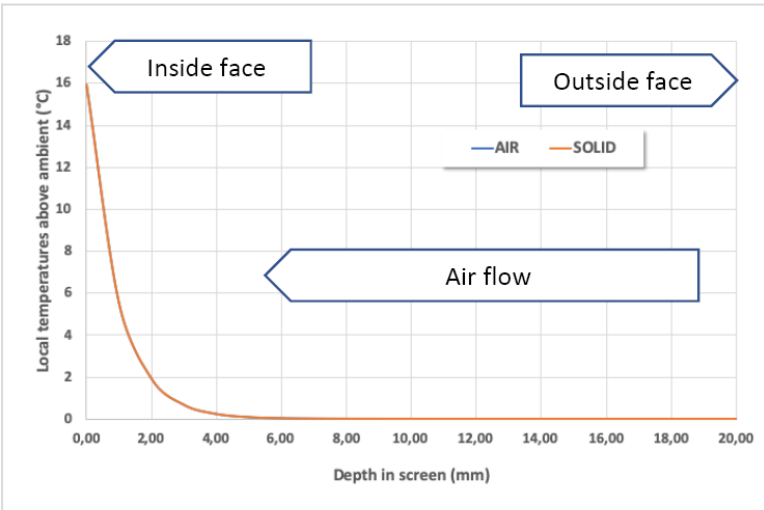

Figure 8. Temperature distribution in a TCS made of ceramic fibers. Irradiation: 1000 $\mathrm{W\,m^{-2}}$, $\lambda = 0.03\ \mathrm{W\,m^{-1}\,K^{-1}}$, $V = 0.05\ \mathrm{m\,s^{-1}}$ and $F = 0.024$. The air temperature is very close to the temperature of the solid so that the two curves are superposed. The temperature is close to ambient through most of the screen thickness.

centerline). The relationship between this local velocity and the average velocity may be affected by many geometrical factors like turbulence, friction on pipe wall, presence of straight lines and bends along the pipe length or other obstacles.
- C_p (J kg^{-1} K^{-1}) is the air heat capacity. The heat capacity varies with the relative humidity.

Appendix A gives a method of calculating the heat capacity as a function of the actual air conditions. The quantity of air that flows through the AFC box per second can be evaluated via different methods:

- Measurement of the air velocity in the inlet pipe connected to the box.
- Direct measurement of the air mass by a mass flow meter.

Different types of flow meters are available. An abundant literature describes the operation of the various sensors [8–16]. Table 1 summarizes some information on the main types of flow sensors.

Table 1. Main types of flow sensors.

Sensor type	Principle	Physical measure	Other parameters for mass flow knowledge	Remarks
Hot wire	Cooling of a heated wire	$k_1\lambda + k_2\sqrt{\lambda\rho V}$	λ = f(T-H)	Local point measure
Ultrasonic	Time of flight of US pulses or Doppler effect	V	ρ = f(P-T-H)	Average V
Orifice plate	Pressure drop through a restriction	1/2 ρV^2	ρ = f(P-T-H)	Average V
Venturi	Bernoulli effect	11/2 ρV^2	ρ =f(P-TH)	Average V
Pitot tube	Bernoulli effect	1/2 ρV^2	ρ = f(P-T-H)	Local point measure
Turbine	Freewheeling propeller	V	ρ =f(P-T-H)	Average V must exceed a minimum value to overcome propeller bearings friction

V is the air velocity (m s^{-1}), ρ the air density (kg m^{-3}), λ the air conductivity (W m^{-1} K^{-1}), P the air pressure (Pa), T the temperature (K), and H is the relative humidity (%).

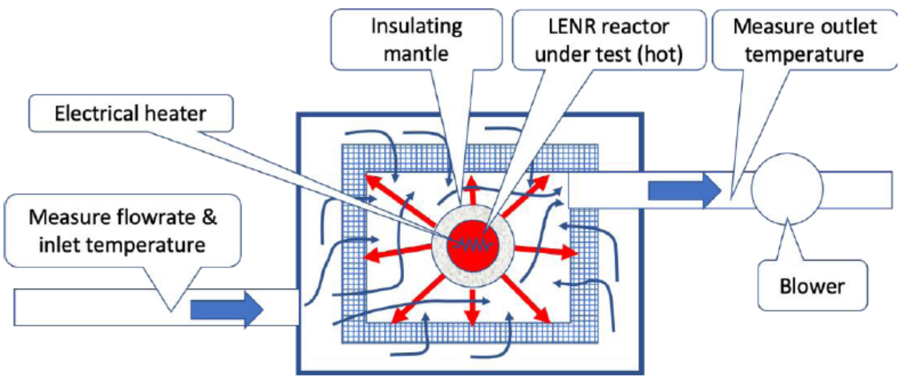

Figure 9. Schematic AFC setup to test a high temperature reactor (with TCS).

Some sensors give the velocity of the gas. The measurement of the mass flow requires the separate determination of the gas density. It depends on the local pressure temperature and humidity. Some sensors directly deliver the average velocity in the pipe. Others measure the velocity at a particular position in the pipe. Groups of sensors are sometimes arranged across the pipe section (e.g. arrays of Pitot tubes).

Mass flow sensors are generally calibrated for a specific range of environmental conditions. If high accuracy is desired the calibration may have to be revisited [17]. The relationship between the velocity measured on a single point and the average flow is influenced by many factors such as gas velocity, level of turbulence, geometrical configuration of the piping arrangement, etc. It is generally specified that long straight pipes must be installed upstream of a flow meter [18,19]. This requirement can be relaxed if flow straighteners are incorporated in the piping design [20–22].

The sensor must be selected for the specific range of expected air velocity. This is particularly true for the types sensitive to the product ρV^2. Venturis or calibrated orifice plates are normally used for the calibration of other flow meter types [11]. In industry the hot wire type is frequently used, for example to control the air/fuel ratio in combustion engines [15].

7.3. Air inlet and outlet temperatures

The other important parameter for the measurement of heat generation is the air temperature difference between the inlet and the outlet. Different temperature sensors are available (thermocouples, thermistors, resistive temperature detectors (RTD)) [23–25]. In the inlet and outlet pipes the airspeed may be important depending on the design. The air temperature sensors must be arranged to measure the stagnation temperature [26].

The air inlet temperature must be as constant as possible. This depends on the laboratory room heating ventilation or air conditioning system performance. In the inlet and outlet pipes the air flow can be made turbulent, but the air velocity is rather low inside the calorimeter box. The presence of the hot reactor creates a plume of hot air that accumulates at the top. The temperature stratification may still be detectable in the air outlet pipe where the outlet temperature is measured, which would introduce incorrect readings. In order to have a valid measurement of the average temperature it is advisable to locate a static mixer in the outlet pipe upstream of the temperature sensor [27,28].

7.4. Evaluation of errors

Any fluctuation of the inlet temperature results in an error in the heat flow measurement. The heat storage capacity of the whole system introduces a time lag on the readings. For a given heat power there is an optimum combination of flow rate and temperature rise in order to maximize accuracy. The theoretical accuracy of air flow calorimetry is discussed based on the fractions of heat carried away by the air flow and heat losses. Any sensor is characterized by a relative error level on the value reading plus a systematic error given as a percentage of the full scale of the measurement.

Let us assume that the average air velocity V is subjected to a systematic error $\mathrm{d}v$ and that the temperature difference ΔT is similarly affected by an error $\mathrm{d}t$. The heat flow value W can be written as

$$W = \rho C_\mathrm{p} S V \Delta T = k V \Delta T, \tag{4}$$

W is measured within the error margin

$$[S(V - \mathrm{d}v)]\,[\rho C_\mathrm{p}(\Delta T - \mathrm{d}t)] < W < [S(V + \mathrm{d}v)]\,[\rho C_p(\Delta T + \mathrm{d}t)]\,. \tag{5}$$

A first order approximation gives

$$S\rho C_\mathrm{p} V \Delta T\left[1 - \left(\frac{\mathrm{d}v}{V} + \frac{\mathrm{d}t}{\Delta T}\right)\right] < W < S\rho C_\mathrm{p} V \Delta T\left[1 + \left(\frac{\mathrm{d}v}{V} + \frac{\mathrm{d}t}{\Delta T}\right)\right]. \tag{6}$$

The relative error is the sum of the relative errors in the different parameters.

The following equations show there is an optimum choice of V to minimize the error. For a given heat flow value W the product $V\Delta T$ is theoretically constant. For a given value of V we have

$$\Delta T = \frac{W}{S\rho C_{\mathrm{p}} V} = \frac{W}{kV}, \tag{7}$$

The relative error dt on ΔT can be written:

$$\frac{\mathrm{d}t}{\Delta T} = \frac{kV\mathrm{d}t}{W}. \tag{8}$$

The overall relative error is then

$$\mathrm{relativeerror} = \frac{\mathrm{d}v}{V} + \frac{\mathrm{d}t}{\Delta T} = \frac{\mathrm{d}v}{V} + \frac{kV\mathrm{d}t}{W}. \tag{9}$$

Figure 10 shows schematically the relative error as a function of V. There is an optimum value of V that depends on W/k, $\mathrm{d}t$ and $\mathrm{d}v$.

7.5. Other sources of errors

Any experimental installation must be thoroughly analyzed to identify all possible secondary sources of errors. An example is given by the presence of the electrical leads connecting the LENR device to the power supply and to the measurement equipment. On one hand Joule heating losses introduce a parasitic source of heat. On the other hand, the metallic wires can extract heat from the calorimeter by conduction. The resultant effect depends on the overall configuration. Another example is the design of the mechanical support of the device inside the enclosure.

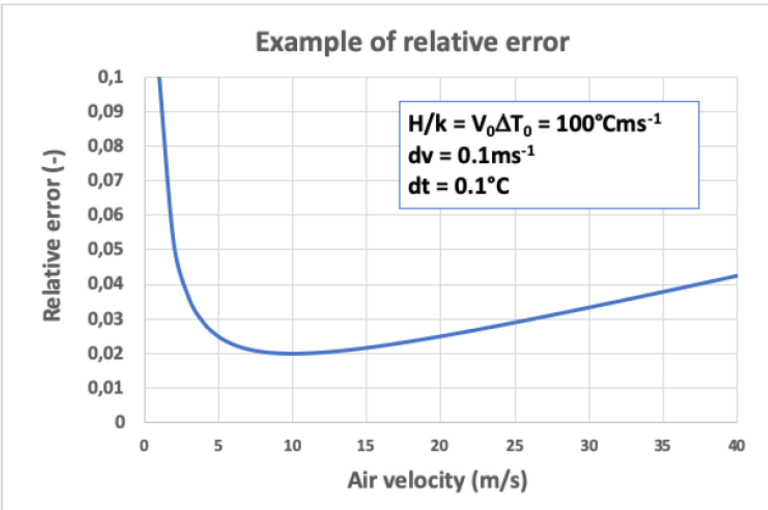

Figure 10. Example of relative error calculated for flow and temperature sensors affected by systematic errors. There is an optimum air velocity that minimizes the error.

8. Calibration

Because so many parameters can affect AFC it may seem difficult to do reliable experiments with this method. In fact, it is fortunately possible to minimize most of the uncertainties with a careful calibration. Calibration is done by monitoring the data obtained during the operation of a known heating power. The power dissipated by an electrical heater can be controlled with great accuracy.

If all AFC parameters are kept unchanged between the calibration run and the LENR test the heat generated by the LENR reactor can be obtained via a relative comparison of the power measures. The relative measurement method is able to deliver accurate results provided the following precautions are taken.

– Heat losses must be known. It is best to minimize the heat losses. The lower the heat losses the lower the sensitivity to external conditions. The TCS configuration that basically eliminates all heat losses is recommended.
– A run takes a long time, typically several hours because equilibrium must be reached before any measurement. During this time the air pressure and humidity may have changed. No calibration can prevent a modification of the air heat capacity. This value must be frequently checked during all experiments.

9. Conclusion

The AFC method can be utilized to measure the generation of heat of an LENR reactor. It is relatively cheap to set up and can be applied to reactors of any size and surface temperature. Its use is restricted to the testing of reactors that work continuously because thermal equilibrium must be reached to make valid measurements.

The AFC system must be designed to minimize the heat losses. The TCS configuration introduced here is an interesting solution. A thorough calibration procedure is essential to minimize the influence of errors on mass flows and temperature differences. The heat capacity of the air must be calculated separately.

Appendix A. Heat Capacity of Humid Air

AFC requires the knowledge of the heat capacity of the air that cools the sample. Any error on this parameter has a direct influence on the heat power measured. It is therefore necessary to introduce in the calculation of the results a precise value of the heat capacity.

The specific heat capacity of air for constant pressure C_p depends on several parameters. This appendix provides a method of determination of C_p for conditions that correspond to AFC needs, at ambient pressure and temperatures encountered in laboratories.

Calculation utilizes the C_p of dry air and the theoretical influence of humidity, as explained below (Table 2).

These data make it possible to write Eqs. (A.1) and (A.2):

$$\text{Dry air: } C_{\mathrm{pa}}(\mathrm{kJ\,kg^{-1}\,K^{-1}}) = 1.0037 + 3\times10^{-5}\,t + 3\times10^{-7}\,t^2, \tag{A.1}$$

Table 2. Specific heat capacities of dry air and water vapor (sources: [29,30]).

T (K)	t (°C)	C_pa dry air ($\mathrm{kJ\,kg^{-1}\,K^{-1}}$)	C_pw vapor ($\mathrm{kJ\,kg^{-1}\,K^{-1}}$)
250	–23	1.0031	1.855
275	2	1.0038	1.859
300	27	1.0049	1.864
325	52	1.0063	1.871
350	77	1.0082	1.88

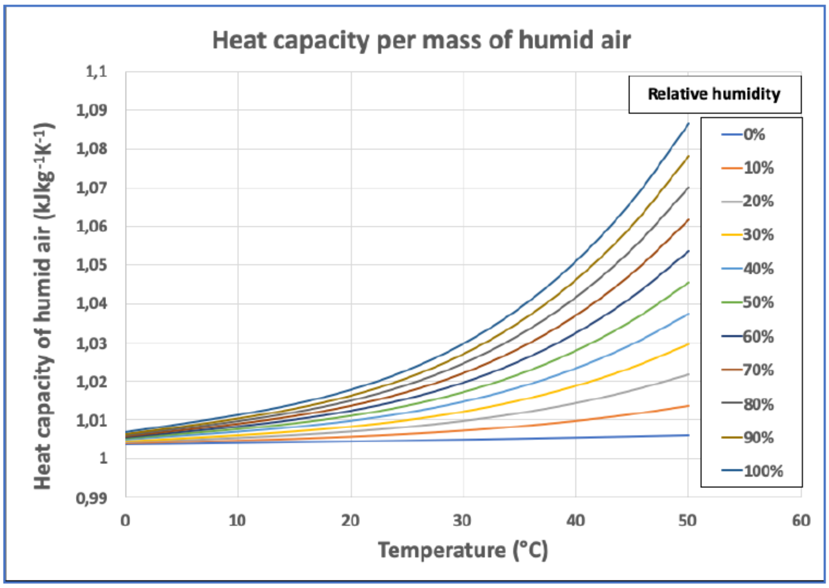

Figure 11. Specific heat capacity for a mass of humid air.

$$\text{Water vapor: } C_{\text{pw}}(\text{kJ kg}^{-1}\,\text{K}^{-1}) = 1.8584 + 2 \times 10^{-4}\,t + 10^{-6}\,t^2. \tag{A.2}$$

The coefficients of determination $R^2$of the above equations are respectively 0.9999 and 0.9997. The C_p of dry air varies slightly with the temperature. The pressure has no influence under our conditions. The heat capacity of water vapor is larger than dry air. The air humidity must be taken into account.

Let us assume the following air conditions:

- laboratory pressure: P (Pa),
- inlet temperature: t (°C),
- relative humidity: H (%).

Table 3. Vapor pressure at saturation in humid air (source: [31]).

t (°C)	Vapor saturation pressure P_s (Pa)
0	603
10	1212
20	2310
30	4195
40	7297
50	12210
60	19724

The vapor pressure at saturation (H =100%) is linked to the temperature as shown in Table 3. The saturation pressure P_s can be described by Eq. (A.3):

$$P_\mathrm{s} = 568.62 + 75.215t - 1.1693t^2 + 0.0871t^3. \tag{A.3}$$

The coefficient of determination R^2 of this formula is 0.9999. For a humidity H the actual partial pressure of the vapor is

$$P_\mathrm{w} = P_\mathrm{s}H/100. \tag{A.4}$$

The partial pressure of dry air P_a is then

$$P_\mathrm{a} = P - P_\mathrm{w}. \tag{A.5}$$

For a volume of air of 1 m^3 under the conditions used for the calculation the masses of air M_a and water vapor M_w are:

$$M_\mathrm{a} = 1.294(P_\mathrm{a}/101325)273/(t + 273), \tag{A.6}$$

$$M_\mathrm{w} = 0.803(P_\mathrm{w}/101325)273/(t + 273). \tag{A.7}$$

The volumetric heat capacity is

$$C_\mathrm{p} = M_\mathrm{a}\, C_\mathrm{pa} + M_\mathrm{w}\, C_\mathrm{pw}(\mathrm{kJ\,m^{-3}\,K^{-1}}). \tag{A.8}$$

The mass of the gases is $M_\mathrm{a} + M_\mathrm{w}$. The specific heat per mass of humid air is

$$C_\mathrm{p} = \frac{M_\mathrm{a}\, C_\mathrm{pa} + M_\mathrm{w}\, C_\mathrm{pw}}{M_\mathrm{a} + M_\mathrm{w}}(\mathrm{kJ\,kg^{-1}\,K^{-1}}). \tag{A.9}$$

Figure 11 shows the specific heat capacity as a function of the temperature and humidity. Figure 12 shows the volumetric heat capacity as a function of the temperature and humidity.

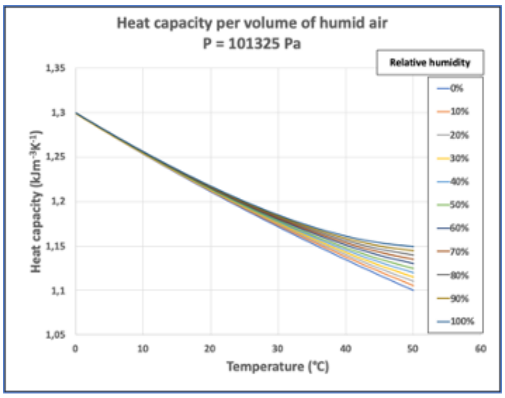

Figure 12. Volumetric heat capacity of humid air for a pressure of 101325 Pa.

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