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Research Article

Mass and Heat Flow Calorimetry in Brillouin's Reactor

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Abstract

Brillouin Energy (BEC) has continued performing calorimetry measurements on the metal (e.g. Ni)/ceramic/Cu coated ceramic tube (catalyst) in a H_2 atmosphere with nanosecond pulses applied across the coatings. The Energy Research Center (ERC) has been examining and verifying BEC's calorimetry for over 18 months since 2 of the calorimeters have been moved from SRI International to BEC's laboratory. We have continued our testing of new materials, material fabrication techniques, and electrical stimulation methods to produce excess power and energy output. By applying fast pulses of several hundred volts and tens of nanoseconds long, the current follows the "skin-effect" principle and is concentrated at the outer metal–ceramic interface but returns through the bulk of the Cu. Two stimulation methods were used – steady-state and dynamic. In the steady-state method, the pulse power is measured directly using fast oscilloscopes that record the voltage across the catalyst and a shunt resistor in series with the catalyst. The resistance of the shunt resistor is measured accurately under DC and pulse conditions. The input pulse power is determined by multiplying the calculated root-mean-square voltage and current and recorded every 10 s. Using a version of the system identification (SI) heat-flow model designed specifically for the BEC calorimeter, the power reaching the five temperature sensors is determined during simultaneous continuous ramps of both heater and pulse powers. The power emanating from the catalyst is determined during sequences of less frequent, longer duration, low voltage pulses (LVP) and compared to that found using more frequent, shorter duration, high voltage pulses (HVP). The power determined during the less frequent LVP is set as the input power during that sequence. The power of the stimulation pulses during the more frequent HVP sequences is maintained equal to that during the less frequent LVP. Then the calculated power output from the tube is divided by that calculated during the reference sequences, giving a so-called coefficient of performance (COP). We have also used mass flow calorimetry to determine COP. Low voltage, long pulses are chosen to match the input power from high voltage, short pulses. The low voltage pulses are not thought to stimulate LENR, while the high voltage pulses are. This provides a method to compare matching input power under conditions that stimulate LENR with conditions that do not. Any excess heat detected from the high voltage pulse condition is considered to be generated by LENR rather than resistive heating.
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1. Introduction

Since 2012, first SRI International (SRI) and later Energy Research Center (ERC) have been performing tests on two different versions of Brillouin Energy Corp.'s low-energy nuclear reactors (LENR) [1]. We have operated these reactors independently in an attempt to verify results that Brillouin has found with these reactors and others like them. We have also monitored and advised Brillouin on the results from identical reactors operated by Brillouin in their own laboratory. This paper reports on the verification and validation of results [2] obtained in Brillouin's laboratory since the last report. Brillouin has indicated that it has designed the control systems in its reactors to drive the underlying physics of LENR, as described in its Controlled Electron Capture Reaction (CECR) hypothesis [3]. The CECR hypothesis explains how BEC believes that their reactors generate controlled LENR reaction heat. Our study did not attempt to prove or disprove Brillouin's CECR hypothesis.

The systems tested and described in this report consist of three parts: catalysts, reactors, and calorimeters. The catalysts are the reactive components of the system. The reactors provide the environment and stimulation that causes the catalysts to produce reaction heat. The calorimeter is used to measure the thermal efficiency and absolute heat produced by the catalyst-reactor system. The calorimeter was designed by both SRI and Brillouin personnel to be perfectly matched to the reactor. The results from four of these reactors are described in this report.

Brillouin's system design utilizes both SI and mass flow calorimetry, in which a heat spreader catalyst and reference temperatures are held constant by varying the input heater power while applying different types of stimulation that also input power to the reactor/calorimeter. This "dynamic" method of analysis allows us to analyse all power entering or affecting the catalyst as well as all power emanating from the catalyst based on differential equations describing temperature and power variations. While this requires several days of calibration and up to 40 h of excitation to verify that calibration, it allows for the testing of 12-parameter variations per hour versus one or two in the traditional mass flow, steady-state method.

2. Experiment

2.1. Reactor design

The catalyst consists of metal and ceramic coatings applied to a ceramic substrate, which in some configurations includes a heater and thermocouple. Generally, these coatings alternate between a hydrogen-absorbing metal and an insulating ceramic. The exact size, shape and composition of this catalyst is considered proprietary at this time.

Other designs have used more or fewer layers. All of the layers are porous, allowing the gas(es) in the reactor chamber access to all coatings. A heater, if present, and a thermocouple are located in the axial and radial center of the substrate. The power to the heater is measured directly from the voltage and current supplied by the direct current (DC) power supply. A schematic diagram of the reactor/calorimeter system is shown in Fig. 1. A photograph of the reactor internals is shown in Fig. 2.

2.2. Measurement

The catalyst is stimulated by sending pulses between the outer layer or layers and the inner copper layer. The nature of the pulses is such that its current travels primarily on the surface of the metal in contact with the ceramic (the "skin effect") [4]. This effect is caused by the very fast rise time of the pulses and is dependent on the magnetic permeability of the metal. Although the skin effect is present on both surfaces of a metal, in a multi-layer system the greatest current is passed at the interface with the greater dielectric [1], in this case the ceramic. An example of this pulse design, which Brillouin refers to as a "Q-Pulse", is shown in Fig. 3. The pulse width presently used is from $\sim$30 to 10,000 ns with a duty cycle normally of less than 1%. More detail on the pulse trains are shown here [3]. All catalysts are measured

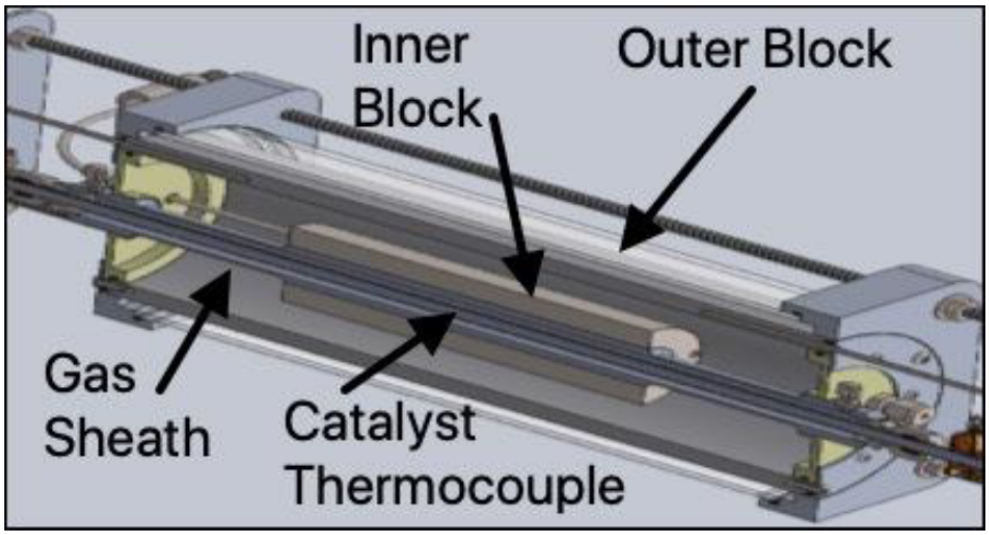

Figure 1. Cut-away schematic drawing of isoperibolic reactor.

using a "Hi-Pot" tester before use. Any one that shows measurable current when 500 V is passed between the two metal layers is rejected. Any voltage breakdown would reduce the possibility of the current pulse passing the complete length of the catalyst. As such, any capacitor discharge is avoided.

The stimulation power imparted to the catalyst is measured using a circuit shown in Fig. 4. The pulse is generated

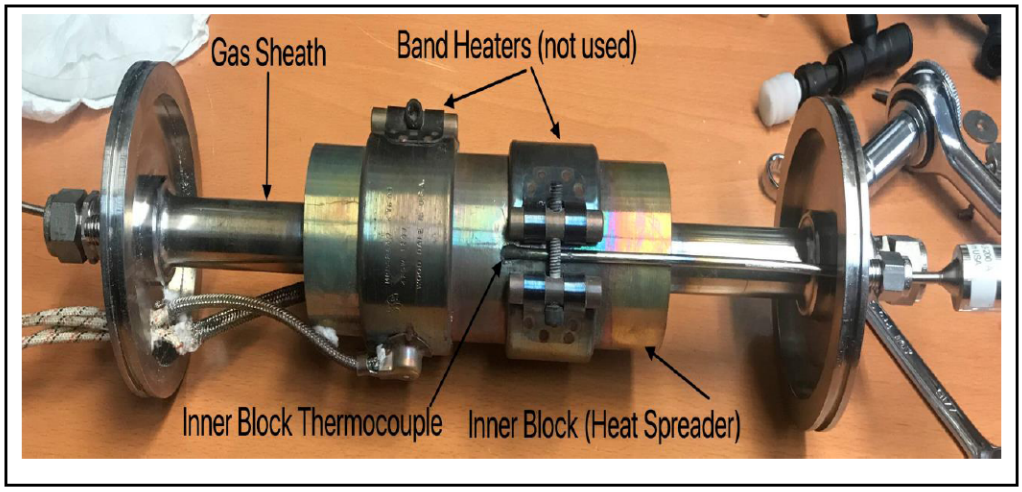

Figure 2. Photograph of reactor internals.

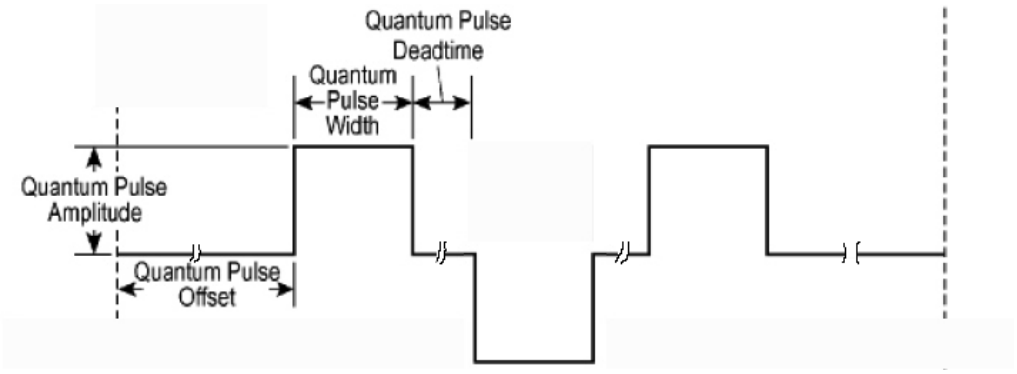

Figure 3. Example of Brillouin's "Q-Pulse".

by a proprietary Q-Pulse board and delivered to the catalyst using series and termination resistors that help match the load impedance to that of the pulse board output. Using a high-speed oscilloscope, the voltage across the end of the catalyst nearest the pulse board (V_1) is measured as well as the voltage across the opposite end of the catalyst (V_2) across the termination resistor (Z_{term}). The Z_{term} also acts as a current measuring resistor so the current is calculated as V_2/Z_{term}. The root mean square (rms) voltage across the Z is then converted to the rms current. The system is designed to be a "well matched" transmission line with a characteristic impedance near 2.0 Ω and verified using a time-domain reflectometer.

The power imparted to the catalyst is determined using the red and blue voltage traces shown in Fig. 5. The difference between the two voltage traces is calculated after aligning them in a way that minimizes the time difference. (The time difference, which may be due to the RC time constant of the system or simply the propagation speed of the pulse, is approximately 5 ns or approximately 0.3 c, where c is the speed of light.) This overestimates the power imparted to the catalyst by a small amount since any phase lag between voltage and current would impart less input power. The current calculated from V_2 is shown in black and the product of it with the voltage difference (power) is shown in green. It has been shown that the power calculation is essentially the same (within measurement error) whether it is calculated by multiplying the current and voltage plots point by point or by multiplying the calculated

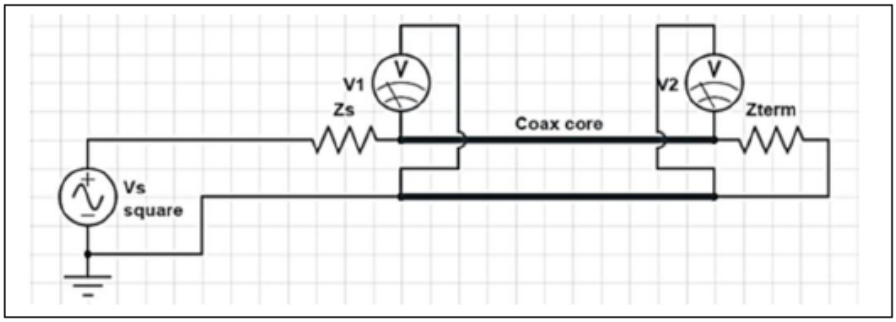

Figure 4. Pulse power measurement circuit.

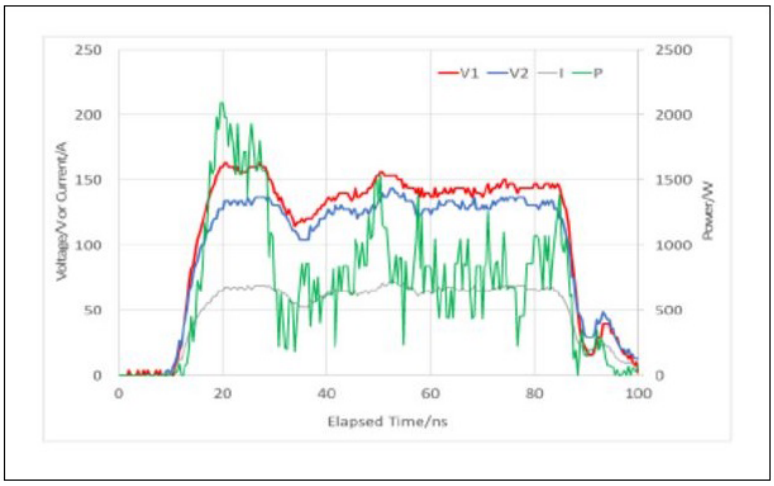

Figure 5. Measurement of the Q-pulse power across the catalyst.

rms voltage by the rms current. This calculated power is referred to as Core Q Power.

In compensation calorimetry the heater power is varied to keep either the catalyst or inner block at constant temperature, which generally also keeps the other at a constant, but slightly different, temperature. The difference between the heater power with and without stimulation determines the effect of the stimulation. If this difference is greater than the stimulation that reaches the catalyst, then energy is being produced in the catalyst. Approximately 70 different parameters are collected allowing for calculation of Reaction Power (the power produced by the process induced by the pulse stimulation). Several calculation methods are possible from these parameters. In addition, two different stimulation sequences are used. In Section 2.4, we describe these two sequences and the calorimetry method used for each of them.

2.3. Operation

A description of the data acquisition system with a copy of the graphical interface has been described earlier [2]. The program has several panes allowing for control of temperature, pressure, pulse voltage, pulse power, pulse width, and pulse repetition rate and gas composition. The program also collects the heater power, the pulse power at the generator (as well as at the catalyst), all temperatures, water flow rates, and gas pressure. The concentration of hydrogen and oxygen in the argon blanket are collected and measured. In all, more than 70 different parameters are collected and stored every 10 s. A sequence file can be used to automatically change any or all of the input parameters at specified intervals over a multi-day or multi-week period.

The sheath containing the catalyst is operated with a static fill of hydrogen, and occasionally helium or argon, gas held at constant pressure up to 15 bar. The temperature of the catalyst, and its substrate, is held constant using the embedded heater and thermocouple and controlled from 100°C to 600°C. The outer block (outer cylindrical perimeter of the calorimeter) temperature is held at 25°C using water flow from a Neslab® recirculating constant-temperature chiller.

The power emanating from the Q-pulse generator board, or that applied directly to the catalyst, is held constant

as chosen by the program's front panel or the sequence file. Generally, the pulse amplitude (voltage) and pulse width are chosen. The repetition rate is adjusted automatically to maintain the chosen pulse power or temperature. Only a minor fraction of this power from the generator board reaches the catalyst as most of it is lost as heat in the termination resistor. This is necessary to get an accurate measure of energy actually dissipated in the catalyst and to match the load impedance to that of the generator thus preventing reflections that could cause measurement errors. Of that reduced power only a portion of it influences the heater power as explained in Section 2.2. The actual pulse power is measured directly via the methodology presented above.

During this time period several stimulation methods were tried to find one that can act as a blank (no excess power) using similar Core Q Power. Ideally these methods need to be compatible with the data collection's software's calculation designed for the low duty cycle Q-Pulse square waves and not require hardware changes. Some of the methods tried were: (1) straight sine waves; (2) low duty cycle square waves; (3) large pulse widths with long rise times. Ultimately, calibration runs used Q-Pulse parameters that were known not to produce LENR heat (low voltage, long length pulses at lower repetition rates) but impart the same power to the catalyst as parameters expected to show LENR heat (high voltage, short length pulses at higher repetition rates).

Operating in power compensation mode, the computer generally keeps the heat spreader (inner block) temperature constant at its set point. This generally keeps the calorimeter output power constant. When power is imparted from the Q-Pulse, the heater power is reduced, or removed completely to compensate and maintain a constant temperature. Hence, the catalyst substrate temperature and the inner and outer block temperatures are all held constant while using the same gas. When the inner block temperature is held constant the output mass flow calorimetry power reaches the same output power whether using heater or pulse input power. This allows for calibration using only heater power. When using lower voltage, lower repetition rate pulses, the calorimetric power is equal to that measured using only the heater.

In addition to applying DC power to the heater inside the tube, DC current was occasionally passed only through the outer metal coating for thermal calibration. Operating at constant gas pressure, a sequence stepped the reactors from 100°C to 300°C in 50°C intervals. At each temperature a given DC power was applied to the outer metal coating on the substrate, as opposed to pulses driven between the outer metal and Cu coatings. This process was then repeated but applying constant power pulses between the Cu and outer metal while varying pulse width at each temperature. The pulse repetition rate was adjusted at each temperature to keep the temperature constant.

Two major methods of operation were employed, each requiring a different analysis method. The first method operated with the reactor at a steady-state temperature and input powers, which we refer to as the mass flow calorimetry (MFC) method. In our second approach, the heat flow (HF) method, we calibrate the system using heater steps as described above, but measure the output power using redundant thermocouples situated at three different locations from inside the reactor catalyst's substrate to the outer reactor boundary. The HF method was developed to allow for many Q-pulse parameters to be tested in less time.

2.4. Analysis

The earlier report [5] describes the two different analysis methods employed in the effort. Here we describe the stimulation and analysis methods employed most recently.

2.4.1. *MFC method*

The steady-state stimulation method was now operated in MFC mode, where the computer kept the temperature constant at either the catalyst substrate or the inner block. Then power was imparted from the Q-pulse replacing the heater power and adjusting the pulse repetition rate automatically to keep the inner block at the same temperature maintained

using the heater. Hence, when the inner and outer block temperatures are held constant, the substrate temperature will respond to the stimulation. The output power (calculated from the water flowing through outer block) did not change as the input power compensates for the total power emanating from the catalyst. The total output power included the stimulation power and the power due to reaction heat (i.e. LENR power).

In this method heater power necessary to maintain the inner block at constant temperature for four hours without Q-pulses present was applied. We realize that only a fraction of the heater power may be imparted to the catalyst because the heater/thermocouple combination has temperature-dependent losses to the rest of the calorimeter and to the environment. The steady state is achieved during the 4-hour heater step and the inner block temperature remains constant during the subsequent Q-Pulse steps. During these Q-Pulse steps the system is instructed to apply chosen pulse width and pulse amplitude at each step while the system adjusts the repetition rate as needed to maintain constant inner block temperature. Figure 6 shows an example of a heater calibration run. The 70% efficiency has been improved as the calorimeter has been modified to capture more of the input power. The latest analyses use a temperature-dependent calorimeter efficiency.

As the thermocouple inside the catalyst substrate is more closely coupled to the heater, its temperature is hotter when using the heater than when applying pulses even though the inner block is held constant because the thermocouple is imbedded in the heater assembly. Since both of these input power steps are allowed to achieve a steady state, the calorimetric efficiency of the Q-Pulse power is taken to be equal to thermal efficiency of the heater at the same temperature. As expected, the MFC output power varies with the inner block temperature such that the source of the heat does not affect the output power at the same inner block temperature.

Another calibration was performed using DC joule heating along the length of the metal outer coating. It is assumed that DC current will not stimulate the MH_x material to yield excess power as proposed to happen with the Q-Pulses.

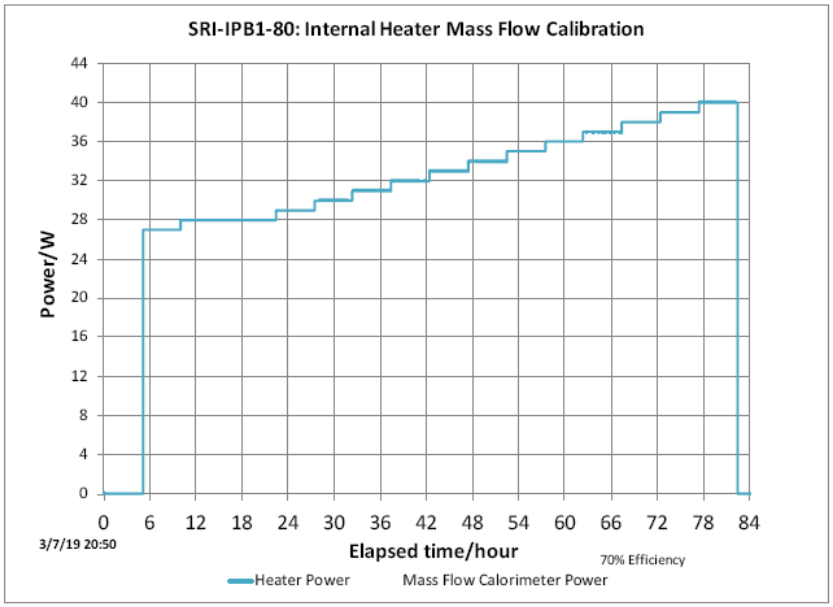

Figure 6. Reactor calibration using a heater inside the reactor tube. The MFC power matches best the input power when a 70% efficiency of the heater power is taken into account.

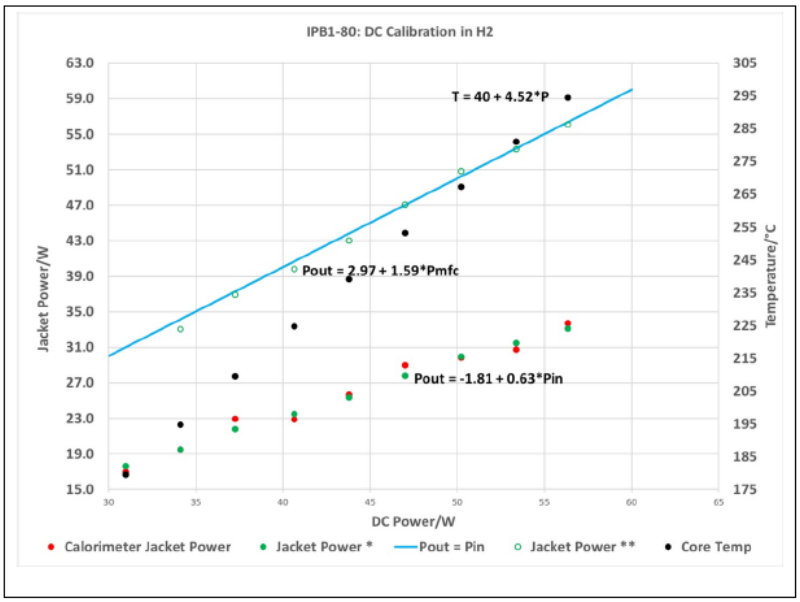

Figure 7. Reactor calibration using DC joule heating along the metal outer coating.

A summary of the DC heating steps is shown in Fig. 7 where input power is plotted on the horizontal axis and output power is plotted on the left vertical axis. The red dots are an average of the final 5 min of the raw calorimeter output power taken at the end of each power step. The green dots are that same power adjusted for the effect of the diurnal change of room temperature. The green circles are the output power adjusted for calorimeter efficiency to best fit the $P_{\text{out}} = P_{\text{in}}$ blue line. The black dots represent the temperature inside the catalyst substrate plotted against the right vertical axis.

Using pulse stimulation and inputting the same power, or holding the same block temperatures, as used in the calibration we use the efficiency calculated from the calibration to calculate the ratio of $P_{\text{out}}/P_{\text{in}}$. Also, using low voltage and high voltage steps at same power we can examine the effect of different pulse amplitudes and width. We have examined different pulse amplitudes and lengths at different temperatures and concluded that the lower amplitude, longer length pulses result in less output power. We then call this our calibration stimulation, even though it may not produce zero excess power, but yields conservative excess power measurement.

2.4.2. *HF method*

The HF method employs a model with several components, each representing individual components of the calorimeter, shown schematically in Fig. 8. This analysis utilizes a simplified version of the system identification (SI) model reported by Berlinguette and Fork [6–8]. Linkages between these components (and from a component to the reference room temperature) are either conductive or storage. Temperatures are on the inside of the catalyst substrate and on the outside of the cylindrical heat spreader (inner block). The five differential equations in time shown in Eqs. (1)–(5), model the heat imparted to the catalyst using a function of the difference of the catalyst and inner block temperature, a function of the ability of the substrate and inner block to store heat, and the difference between the substrate and

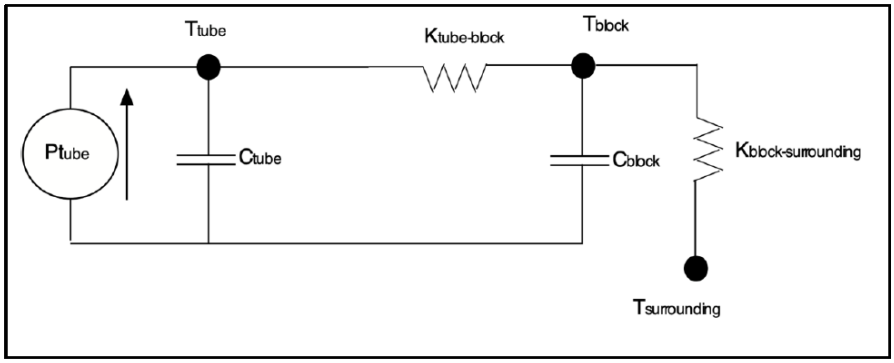

Figure 8. Heat flow calorimetry model of isoperibolic reactor, where "Tube" refers to the catalyst.

ambient temperatures. Each of these four components has three coefficients, each in the form of a third order equation. These coefficients are determined by fitting the temperature data to the actual power measured using low voltage pulses or heater power. The model then yields a simple set of equations that can be solved analytically for input power, being equal to output power during low voltage pulses or joule heating.

$$\mathrm{d}T_{\mathrm{tube}}/\mathrm{d}t = (1/C_{\mathrm{tube}})(P_{\mathrm{tube}} - k_{\mathrm{t-b}}(T_{\mathrm{tube}} - T_{\mathrm{block}})), \tag{1}$$

$$\mathrm{d}T_{\mathrm{block}}/\mathrm{d}t = (1/C_{\mathrm{block}})(k_{\mathrm{tube-block}}T_{\mathrm{tube}} - T_{\mathrm{block}}) - k_{\mathrm{block-surrounding}}(T_{\mathrm{block}} - T_{\mathrm{surrounding}})), \tag{2}$$

$$P_{\mathrm{in}} = P_{\mathrm{tube}}(\text{pulse, DC or internal heater}), \tag{3}$$

$$P_{\mathrm{out}} = k_{\mathrm{block-surrounding}}(T_{\mathrm{block}} - T_{\mathrm{surrounding}}), \tag{4}$$

$$P_{\mathrm{stored}} = C_{\mathrm{tube}}(\mathrm{d}T_{\mathrm{tube}}/\mathrm{d}t) + C_{\mathrm{block}(}(\mathrm{d}T_{\mathrm{block}}/\mathrm{d}t). \tag{5}$$

These coefficients are represented as four simple 3-coefficient binomial equations, yielding 12 possible parameters. These parameters are then used to calculate the amount of heat emanating from the catalyst during an attempt to produce LENR heat. A comparison between the calculated power emanating from the catalyst during an active run and that from the calibration run at the same temperature and with the same Core Q Power is used to determine the amount, if any, LENR heat was produced. The computer application MatLab® is used to determine the best fit parameters, although other applications can be used to solve these simple equations.

3. Results and Discussion

A tabulation of all experiments run to date in the IPB calorimeters is available on the Brillouin Energy web site [5].

Table 1. Summary of COP calculations from mass flow calorimetry runs.

Temperature (°C)	COP IPB1
200	1.30
220	1.41
260	1.46
270	1.26
275	1.40

3.1. Mass flow calorimetry results

The runs detailed in this analysis of MFC runs generally used a 100 ns pulse width with similar Q power on the catalyst at different voltages. The data acquisition and control system kept the Core *Q* Pow relatively constant at each temperature.

Table 1 summarizes the COP results from recent MFC runs performed in two identical reactors. COP was calculated by dividing the $P_{\mathrm{out}}/P_{\mathrm{in}}$ from the reactor with an active catalyst and one with an inactive catalyst. These catalysts were chosen based on previous results. Comparing the active catalyst to the inactive catalyst the COP was between 1.26 and 1.41 with no obvious dependence on temperature. The COP's were calculated from the average $P_{\mathrm{out}}/P_{\mathrm{in}}$. of several runs at the same temperature. A total of 65 $P_{\mathrm{out}}/P_{\mathrm{in}}$. calculations at different temperatures were used to create Table 1. Output powers from less than 10 W at lower temperatures to approximately 30 W at the highest temperatures were measured.

3.2. Heat flow calorimetry results

Figure 9 shows the results of a calibration run using the HF method. The left chart plots the measured and calculated temperatures from 11 steps in heater power. The right chart shows the control and measured heater power during this calibration run. Although the heater power quickly reaches a steady state, the time constant of the calorimeter prevents its temperature from reaching the steady state. In order to perform this experiment using MFC we would need to wait three time-constants which would take much longer than the time needed in this HF run. By solving Eqs. (1)–(5) using the measured temperatures and input power we find the coefficients shown in Table 2. Using these coefficients to calculate the temperatures from the known powers yields plots of both block and substrate temperatures indistinguishable from their respective measured values.

Figure 10 plots the input power and output power calculated using the measured temperatures and Eqs. (1)–(5) during an active run. It is obvious that this analysis yields a COP of up to 1.5 at higher temperatures and power.

Table 3 lists the coefficients found from a calibration run on a different catalyst in a different reactor. For this active excitation run the *Q*-pulse power was scanned from 0 to 43 watts in a sine-squared function versus time. Using the coefficients from Table 3 the output power curve was calculated from the measured temperatures. The input power and calculated output power are plotted versus time in Fig. 11. It can be seen from this plot that the COP was greater than 1.5.

Table 2. Heat flow coefficients found from calibration run in Fig. 9, where "Tube" refers to the catalyst.

Coefficient	Value	Coefficient	Value	Coefficient	Value	Coefficient	Value
ctube0	106.87	cblock	4213	Kb-s	0.22	Kt-b	0.31
ctube1	–0.403	cblock	–6.1	Kb-s	0.000489	Kt-b	–0.00030
ctube2	0.000461	cblock	0.0107	Kb-s	–1.92E-0	Kt-b	6.62E-07

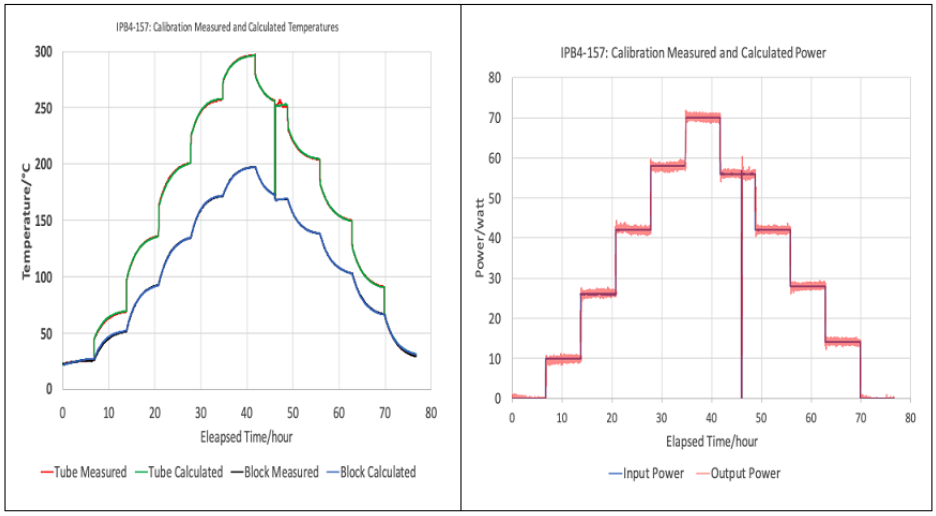

Figure 9. Calibration run using the heat flow method.

4. Conclusions

LENR can produce thermal power when hydrogen-absorbing, catalytic metal-coated substrates are stimulated using fast rise-time pulses. These experiments operated in H_2 gas from 200°C to 350°C. Comparative thermal measurements were performed between heater-only power and heater and pulse power. These runs were performed in isoperibolic

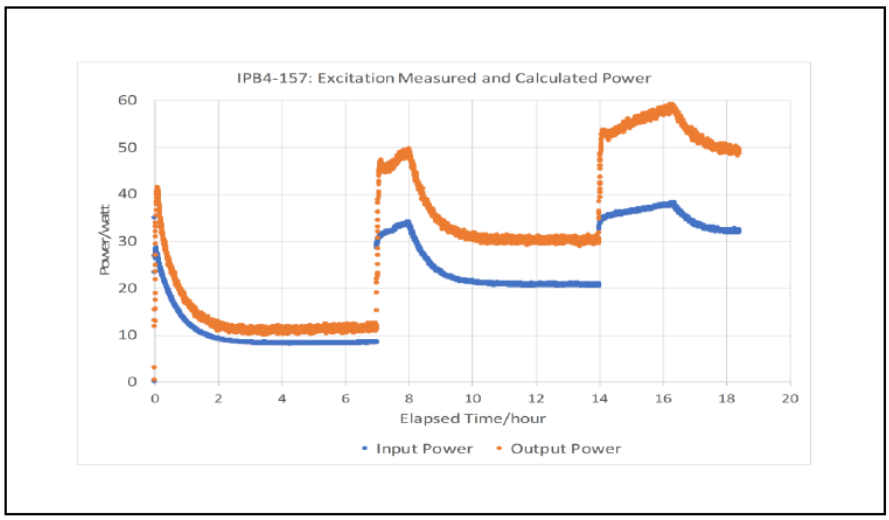

Figure 10. One example of an excitation run using the heat flow method.

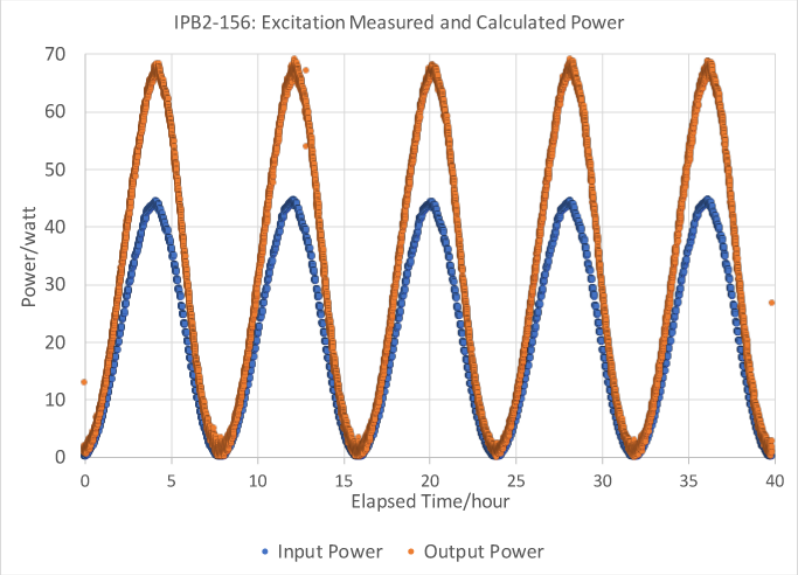

Figure 11. Another example of an excitation run using the heat flow method.

Table 3. Heat flow coefficients found from calibration run in a different reactor.

Coefficient	Value	Coefficient	Value	Coefficient	Value	Coefficient	Value
ctube0	$3.76\times10^{+01}$	cblock	$2.16\times10^{+04}$	Kb-s	4.00×10^{-01}	Kt-b	1.80×10^{-01}
ctube1	-9.14×10^{-02}	cblock	$-9.79\times10^{+01}$	Kb-s	-5.62×10^{-04}	Kt-b	2.54×10^{-04}
ctube2	1.22×10^{-04}	cblock	1.31×10^{-01}	Kb-s	1.15×10^{-06}	Kt-b	1.93×10^{-07}

calorimeters operated in steady-state mode, where the heater adjusts its power to keep the inner block (heat spreader) temperature constant. After stepped constant-power calibrations, non-steady-state excitation pulse powers were imparted to the outer metal coating on the substrate.

Over 600 runs were performed on over 100 different catalysts using different calorimetric methods in four different isoperibolic reactors. Additional catalysts were also tested for other experimental purposes. The reproducibility of recent results has been considerably better than those reported earlier. Earlier reports have shown that catalyst can be transported between different laboratories and using different reactors to achieve very similar positive results.

Calibrations and active runs have recently been performed comparing all thermal output to all electrical power input. Encouraging results have been seen and will be presented in the future.

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