Reflected impedanceometry: a contact-free technique for measuring induced magnetic hysteresis and eddy current heating

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Keywords: RF heating, induction heating, reflective impedanceometry, magnetic hysteresis, eddy current, electromagnetism

Abstract
Reflected Impedanceometry is a new technique that can remotely measure the power absorbed during radiofrequency induction heating. It measures the total system impedance from the phase difference between current and voltage in the electromagnetic field work coil and uses the characteristic impedance of the work coil circuit to infer the heating power transferred into a susceptor bed. Induction heating of susceptor materials within alternating magnetic fields occurs by magnetic hysteresis, eddy currents, Néel relaxation or Brownian relaxation. It shows potential for replacing fossil fuels with renewable electricity in carbon-intensive industrial applications but requires advances in measurement techniques. Results presented here show that reflected impedanceometry accurately measures heating power for both magnetic hysteresis and eddy currents, fulfilling the requirement for measuring induction heating power.

Introduction
Endothermic chemical reactors are traditionally heated using steam generated from natural gas or from its direct combustion. The electromagnetic induction heating of catalysts at radiofrequencies (1 Hz–3 MHz) promises to transform chemical manufacturing by: (a) decarbonizing heating by replacing fossil fuels with renewable electricity [1]; (b) reduction in side reactions and fouling as the catalyst becomes the ‘hot spot’ in the reactor [2–6]; (c) process intensification through volumetric heating and integration in combining the heat transfer and reaction steps; and (d) improved catalyst temperature control by both providing energy directly to the catalyst, reducing the thermal inertia caused by heat transfer restrictions. Catalysts for induction heating could be deposited on the surface of a susceptor material, and there are certain processes where the catalysts might also have a dual function as a susceptor material, such as nickel or iron oxides.

Susceptor materials located within an alternating electromagnetic field are heated by a variety of mechanisms in which the heated bed and the work coil generating the electromagnetic field are inductively coupled. The heating mechanism is dependent on the susceptor material. Electrical conductors are heated through the formation of eddy currents and this mode is sometimes referred to as Joule heating as heat is produced by resistance to these eddy currents in accordance with Joule’s law. Ferri- and Ferro-magnetic materials heat by induced hysteresis at temperatures up to the Curie point, above which they become paramagnetic and thermal energy is sufficient to overcome any internal magnetic energy barriers, reducing the irreversible hysteresis to zero. Recent progress [7] has shown how the application of pick-up coils (magnetometry) can be used to measure the heat generated by magnetic hysteresis but this cannot be extended to eddy current heating. It also requires that the susceptor material or heated catalytic bed are located within the cross section of the pick-up coils which could limit the potential application.
In this work, a highly novel application of impedanceometry called reflected impedanceometry has been developed to measure the power transferred into a bed of susceptor material. Due to inductive coupling between the susceptor and the work coil, the impedance associated with the susceptor bed is reflected into the primary work coil circuit. Reflected impedanceometry uses the measured total system impedance and characterization of the empty work coil to infer the component of real power attributable to the susceptor, and hence the quantity of heat absorbed (figure S1 available online at stacks.iop.org/JPCO/6/095002/mmedia).

The total circuit impedance can be determined in a number of ways, such as by measuring the magnitude and phase difference of the alternating voltage and current across the work coil using a variety of techniques, such as a network analyzer. An established impedanceometry technique, Time Dependent Reflectometry (TDR), can be used to determine the circuit impedance in the specific cases of eddy current heating or the Néel relaxation of superparamagnetic particles. TDR works by applying a voltage pulse to the test circuit, and so cannot be applied to this application of magnetic hysteresis loops which require a continuous AC current [8].

The results from this new technique are validated using pick-up coil magnetometry data for magnetic hysteresis heating, and the theoretical eddy current power for eddy current heating [9–11]. Whereas the pick-up coil method can only be applied to hysteresis heating, reflected impedanceometry can measure the total rate of heat absorption for all induction heating modes. The technique requires only the measurement of instantaneous current and voltage within the work coil and no additional instrumentation is necessary. All measurements are performed external to the heated bed, which is expected to give the technique wide applicability, especially when this technology is deployed at larger commercial scales.

**Description of the reflected impedance method**

The instantaneous power supplied to the induction work coil is the product of the voltage and current flowing in the coil. In a circuit that only contains resistance, all of the alternating current is in phase with the voltage, and energy is continuously dissipated in the form of Joule heating (figure 1(a)). In contrast, in a circuit comprising only an inductance the alternating current lags the voltage by 90° and the two signals are completely out-of-phase. Energy is continuously stored in the inductor’s magnetic field and then returned to the power supply, and there is zero net energy supplied to the circuit from one frequency cycle to the next (figure 1(b)). In a circuit that contains both resistance and inductance, the phase angle between the current and the voltage can be used to infer the relative magnitudes of the inductance and resistance, and this is the basis for the reflected impedance method for determining the particle bed heating power.

![Figure 1](https://i.stack.imgur.com/ExampleACcircuit.png)
Results

Evaluation of reflected impedance for magnetic hysteresis
The heating power of ferri-magnetic maghemite powder was measured by reflected impedanceometry up to 175 °C using a bespoke work coil and heating arrangement (figure 2, refer to SI for experimental details). The synthesis and characterization of the maghemite powder is described in a previous work [7].

Data was simultaneously collected using the 3-coil pick-up coil magnetometry technique which has been described in a previous work [7] and compared to the reflected impedance results. Due to the intensity of heat transfer into the susceptor material, the temperature rise within the susceptor can exceed the response lag time of a thermocouple measuring the bed temperature. A pulse-heating approach was used to ensure that the thermocouple measurement was representative of the sample temperature [12]. Eddy current and magnetic hysteresis heating rates increase with increasing frequency, which can lead to a discrepancy between the sample temperature and the measured bed temperature. The work coil circuit was designed with a relatively low resonant frequency to minimize the thermal lag in the thermocouple measurement of the sample bed temperature.

The work coil impedance was characterized with no susceptor present for temperatures between 50 °C–175 °C and field strengths of 4–16 kA.m⁻¹ at a resonant frequency of 27.8 kHz. These measurements were repeated with a 5.47 g sample of maghemite powder within the work coil and the power absorption was calculated using the method presented in the supplementary materials. The resonant frequency varied in the range 25–27 kHz dependent on the degree of magnetisation and temperature of the sample. The sample magnetisation influences the effective inductance of the work coil circuit and hence the operating resonant frequency. The results are presented in figure 3 alongside the simultaneous pick-up coil measurements. There is good agreement between the magnetometry and reflected impedance techniques across the whole range of field strengths and temperature.

Pick-up coil magnetometry measures the magnetisation of the sample localized to within the pick-up coil cross-sectional area. Reflected impedanceometry measures the real and reactive power supplied to the work coil, which is representative of the total power supplied to the whole bed. Some of the difference in measured heating power between the magnetometry and reflected impedance data can be attributed to the difference between the localized and total bed power measurement. A deviation in the uniformity of field strength or sample magnetic properties within the packed bed will also lead to a difference between the two methods. Figure 4 illustrates the axial gradient in field strength in the empty work coil predicted by finite element modeling. This gradient can lead to errors depending upon the axial location of the pick-up coils and the magnetic sample.
Measurement of eddy-current heating of cylinders

For measurement of eddy current power, the magnetic powder was replaced with cylinders of aluminium alloy 6082 of various diameters. Aluminium is non-magnetic and so heats through the generation of eddy currents only.

In order to validate the experimental results, the eddy current power measurement was compared to the theoretical prediction based on the analytical solution to Maxwell’s equations for cylinders, \([9–11]\) and also the results of a finite element model (FEMM). The results are presented in figure 5 alongside a visualization of the finite element modelling results showing the sample location and the field strength within the coil. There is excellent agreement between the reflected impedanceometry and both the theoretical and modelled values. The average error between the three methods is less than 0.6%, with a maximum error of 7.8% for the finite element model: this is a sufficiently repeatable result and acceptable for the remote nature of this measurement.

Figure 3. Heating power versus temperature measured by magnetometry (filled data-points) and by reflected impedance (unfilled data-points) for 5.47 g of maghemite powder at varying applied field strengths between 6.1 kA.m\(^{-1}\) and 15.9 kA.m\(^{-1}\) at a frequency of \(\sim26\) kHz. Linear lines of best fit are provided as a guide to the eye.

Figure 4. FEMM (Finite Element Method Magnetics) \([13]\) axisymmetric model of the field strength variation for a peak current of 25 A flowing in the work coil at a frequency of 30 kHz. The coil consists of three layers of 13 turns of wire each. The inner diameter of the work coil is 20 mm, the outer diameter is 43 mm and the total length is 56 mm.
Measurement of bed inductance

Further to the measurement of heating power, the reflected impedance technique also provides a measurement of the inductance of the sample, which can be separately determined from the resonant frequency of the circuit. The results of this comparison are presented in figure 6. This change in the combined inductance of the work coil and susceptor has a significant impact on the resonant frequency of the electromagnetic field and that this changes as a function of the applied field strength. Increasing the applied field strength increases the number of magnetic dipoles aligned with the field extent and has the effect of increasing the sample inductance, whereas the generation of eddy currents within the sample has the opposite effect as the eddy currents oppose the changes in external field strength. For magnetic hysteresis, the resonant frequency will fall as increasing field strength increases the inductance of the sample and the resonant frequency is inversely proportional to the square root of
the total inductance. For eddy current induction, the resonant frequency will rise with increasing field strength as the inductance associated with the eddy currents are subtracted from the work coil inductance and the total inductance is lower than that of the empty work coil.

The effective inductance of the magnetic sample arises directly from the magnitude of the magnetisation and volume fraction of magnetic material within the work coil. This can be calculated from the magnetometry data and added to a calibration of the empty coil inductance as a third method of measuring the total system inductance for magnetic samples.

The error between the reflected impedance and resonant frequency methods is 2% for the aluminium sample. The maximum inductance error is 5% between the reflected impedance, resonant frequency and magnetometry approaches for the maghemite sample.

Conclusions

The reflected impedanceometry method has been shown to remotely measure heating power and susceptor impedance with reasonable accuracy for both magnetic hysteresis and eddy-current heating methods. The technique requires only measurement of the work coil current and voltage and thus can be easily implemented for a range of electromagnetic heating applications. Its ability to determine the effectiveness of different heating mechanisms further adds to its versatility. This would be of particular value in systems where a hybrid of eddy-current and hysteresis methods is employed or where materials exhibit both electrical conductivity and ferro-magnetism. The measurement of total power supplied to the susceptor bed in magnetic hysteresis heating is a complimentary method to the measurement through a bed cross section using the magnetometry method.

Results presented here also show excellent agreement in the measurement of inductance between the resonant frequency, reflected impedance and magnetometry approaches, with maximum errors of less than 5%. The resonant frequency of the RF induction system is a critical parameter in the generation of heat within the susceptor bed, and the ability to provide accurate validation of the system inductance for both eddy current and magnetic hysteresis heating mechanisms is an important tool for the design and scale-up of this class of next-generation, sustainable chemical reactors.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.15125/BATH-01186 [14].

One-sentence summary

A novel method is presented for measuring heating power in radiofrequency induction heating for industrial chemical reactors.

Funding

This work was supported by the Engineering and Physical Sciences Research Council grant EP/L016354/1.

Author contributions

Conceptualization, Data Curation, Formal Analysis, Investigation, Methodology, Software, Visualization, Writing—original draft: JPPN

Project Administration, Resources, Validation, Writing—review & editing: JPPN, AKH

Competing interests

Authors declare that they have no competing interests.
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References

[1] Schiffer Z J and Manthiram K 2017 Electrification and decarbonization of the chemical industry. Joule 110–4
[2] Ceylan S, Coutable L, Wegner J and Kirschning A 2011 Inductive heating with magnetic materials inside flow reactors. Chem. - A Eur. J. 171884–93
[3] Muley P D, Henkel C, Abdollahi K K and Boldor D 2015 Pyrolysis & catalytic upgrading of pinewood sawdust using an induction heating reactor Energy & Fuels 297375–85
[4] Liu Y, Cherkesov N, Gao P, Fernández J, Lees M R and Rebrot EV 2017 The enhancement of direct amide synthesis reaction rate over TiO2@SiO2@NiFe2O4 magnetic catalysts in the continuous flow under radiofrequency heating. J. Catal. 355120–30
[5] Houlding T K and Rebrot EV 2012 Application of alternative energy forms in catalytic reactor engineering. Green Process. Synth. 1 19–31
[6] Al-Mayman S I and Al-Zahrani S M 2003 Catalytic cracking of gas oils in electromagnetic fields: reactor design and performance. Fuel Process. Technol. 80169–82
[7] Noble J P P, Bending S J, Sarbahua A, Muxworthy A R and Hill A K 2022 A novel in situ high-temperature magnetometry method for radiofrequency heating applications. Adv. Energy Mater. 121–13
[8] Gresits I, Thuróczy G, Sági O, Kollarics S, Csősz G, Márius B G, Nemes N M, García Hernández M and Simon F 2021 Non-exponential magnetic relaxation in magnetic nanoparticles for hyperthermia J. Magn. Magn. Mater. 526167682
[9] Fawzi T H, Ali K F and Burke P E 1983 Eddy current losses in finite length conducting cylinders. IEEE Trans. Magn. 192216–8
[10] Duquenne P, Deltour A and Lacoste G 1994 Application of inductive heating to granular media: modelling of electrical phenomena. Can. J. Chem. Eng. 72975–81
[11] Davies PJ 1991 Conduction and Induction Heating The Institute of Engineering and Technology; London, UK
[12] Lemal P, Geers C, Rothen-Rutishauser B, Lattuada M and Petri-Fink A 2017 Measuring the heating power of magnetic nanoparticles: an overview of currently used methods. Mater. Today Proc. 4S107–17
[13] Meeker DC 2018 Finite Element Method Magnetics, Version 4.2 (28Feb2018 Build) www.femm.info
[14] Noble J P P and Hill A K 2022 Reflected Impedanceometry: A Contact-Free Technique for Measuring Induced Magnetic Hysteresis and Eddy Current Heating University of Bath Research Data Archive 10.15125/BATH-01186