A LOW COST CALIBRATION SYSTEM FOR HIGH POWER MICROWAVE SOURCES

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Abstract: A simple and low cost flow calorimeter for measurement of microwave power is described. The calorimeter consists of a section of a rectangular waveguide in which microwaves are absorbed by the flowing water. The geometry of the water flowing through the waveguide ensures that only a small fraction of the total microwave power is reflected. The microwave power is calculated from the temperature rise of the water and its mass flow rate. The calorimeter was tested for the pulse and CW microwave power range from 200 W to 1000 W and an accuracy of 5% was achieved.

1. Introduction

An increasing interest in the application of high power microwaves in chemistry, metallurgy and mineral processing demands an accurate method of establishing the value of microwave power delivered by the generating system. Most of industrial and experimental systems are based on pulsed power supplies similar to these used in domestic microwave. For this type of microwave systems three types of power measurement have generally been used [1, 2, 3]. The first type is based on sampling high power microwaves via a directional coupler and measurement with low power microwave equipment. This type of measurement requires directional coupler with precisely known directivity and power meter of good accuracy. This method is often expensive and requires special calibration.

The second type of the system is based on direct conversion of electromagnetic energy into heat in a water filled load. Water circulates usually in a closed thermally insulated circuit where its temperature rise and mass flow rate are measured to obtain the total heat absorbed. The system consists of a glass tube filled with water, which is introduced into a waveguide at a small angle to the incident radiation to reduce the reflection of microwaves [4]. Alternatively, small reflection of microwaves is obtained by cementing inside a waveguide a dielectric window so that the incident microwaves see a small angle water taper [1, 5]. This type of measurement gives an accuracy of about 1 - 3% [1, 6].

The third type of power measurement is based on the calorimetric measurement of microwave power and substituting it with a dc powered heater to obtain the same temperature rise. The dc power used for heating the water is equal to the power of microwave irradiation. This method is one of the most accurate and reaches an accuracy up to 0.1% but requires sophisticated heating and temperature control equipment [2].

In this work a simple, easy to manufacture flow calorimeter is described. Using basic equipment, an accuracy of 5% was achieved for the power range from 200 to 1000 W. The biggest advantage of this system is simplicity and low cost that make this calorimeter attractive for calibration of microwave power sources.

2 Microwave power measurement system

A diagram of the measurement system is shown in figure 1. Microwaves are generated by a variable (0 - 1000 W), low ripple (less than 2%), high stability (less than 1% of output power), 2.45 GHz microwave power supply. This power supply is connected to the directional coupler (Sairem® model BC236) and to the slotted line (Narda® model 224). The system is terminated with a 500 mm long termination section of a rectangular waveguide filled with water. The measurement system is placed on an adjustable lifting table so that the angle of the water taper in the waveguide can be changed. Temperatures of the inlet and outlet water are measured using thermocouple based thermometers (Fluke® model 80TK). The outlet water is collected in a thermally insulated container with low initial thermal capacity and weighed after a measured period of time. The microwave power transmitted in the system is absorbed in the water taper, the geometry of which ensures that only a small fraction of the total power is reflected. The microwave power dissipated in the water is calculated from the water temperature rise, mass of water collected and time during which water was collected.

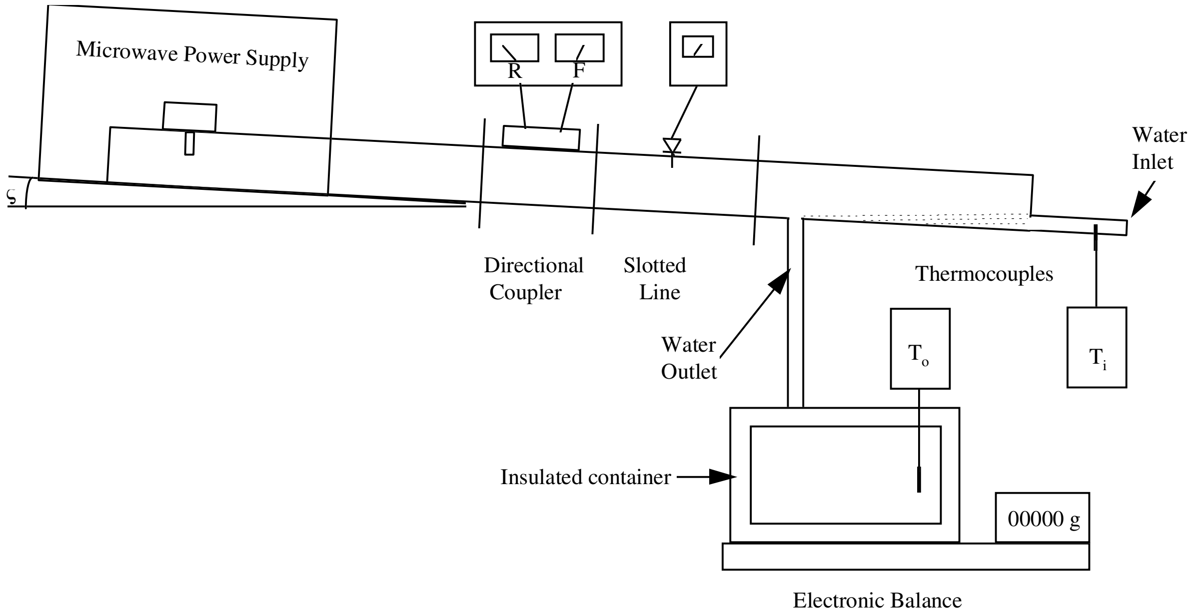

Fig. 1. Schematic diagram of the experimental system.

The waveguide termination section is shown in figure 2. This section was made from WR 284 waveguide ended with a brass plate with a 5 mm diameter water inlet at the bottom edge. The water outlet was a series of 4 mm diameter holes placed inside a 25 mm diameter circle. Transport of water vapour into other parts of the measurement system was prevented by a Teflon® sheet 0.127mm thick and slightly bigger than the waveguide cross-section mounted between the flanges. The termination was thermally insulated with closed pore polyethylene foam to reduce the heat loss to the surrounding.

3. Measurements

Measurements of microwave power were done for three water flow rates, 6, 14 and 46 g/s as a function of the water taper angle, α, in the range from 0.63^o to 15^0. The experiments were carried out using filtered tap water with temperature of about 17^0 C. A period of 30 min was allowed to stabilize the microwave power supply and reduced the heat loss by allowing thermal equilibration of the calorimeter.

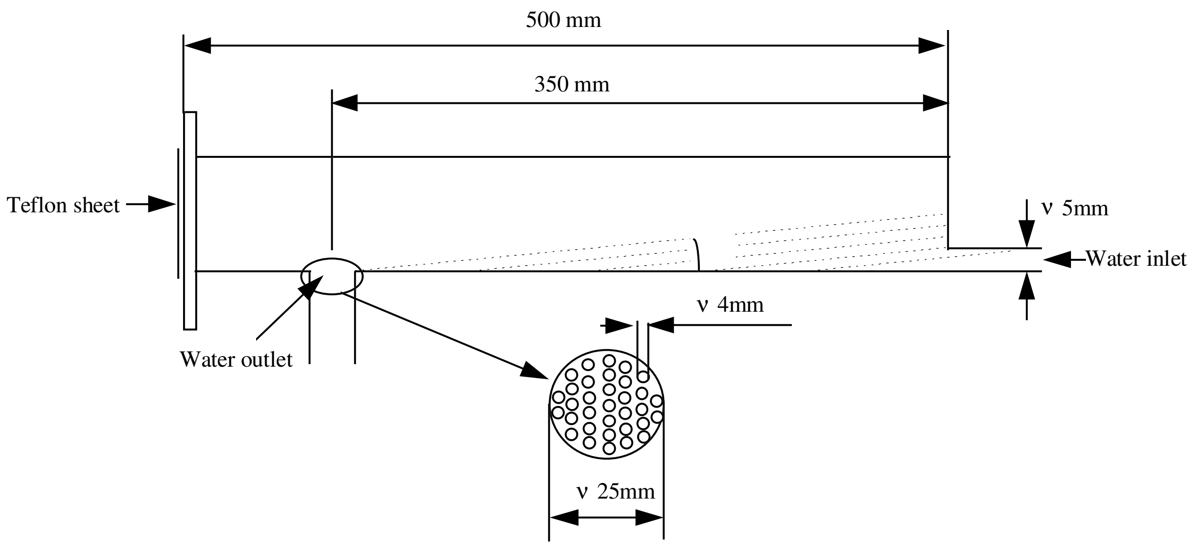

Fig. 2. Diagram of the calorimeter.

The total microwave power calculated from calorimetric measurements was compared with the power measured by the directional coupler. The values of the Volt Standing Wave Ratio (VSWR) were determined for each water taper angle and the water flow rate. These measurements were compared with VSWR measurements obtained using a Hewlett Packard 8410 network analyzer.

4. Calculation of power

The microwave power, P_w, absorbed in the water taper was calculated from the following equation:

$$P_w = \frac{m(c_o T_o - c_i T_i)}{t} \qquad (1)$$

where:

m - mass of water; c_o - specific heat of water at T_o
c_i - specific heat of water at T_i;
T_o - final temperature of water in the container; T_i - temperature of inlet water;
t - time during which water was collected in the container.

Since the water taper was not a perfect termination, some amount of microwaves transmitted in the waveguide was reflected from the water taper. The total power transmitted in the waveguide, P_{tot}, was calculated from the power absorbed in the water and the reflection coefficient, Γ [5].

$$P_{tot} = \frac{P_w}{1-\Gamma^2} \qquad (2)$$

The reflection coefficient was calculated from measured values of VSWR using the following equation [5]:

$$\Gamma = \frac{VSWR-1}{VSWR+1} \qquad (3)$$

An accuracy of ±5% of the total power transmitted in the waveguide was achieved using this experimental system. The accuracy of temperature measurements and variation of inlet water temperature are the major determinants of the total accuracy. The accuracy of temperature measurements was ±0.1° C, but the variation of the inlet water temperature increased that error to ±0.2° C. The average mass of water collected was about 10 kg which was measured with an error of ±5 g. The water was collected on average over a period of about 14 min measured with an error of ±1 s. Thus, the total error of the microwave power dissipated in water, P_w, is about ±4.5%. The inaccuracy of the total power, P_{tot} increased by the error of VSWR measurements which was about ±0.02 for values of VSWR less then 1.3 and leads to overall accuracy of ±5%.

5. Results and Discussion

The effect of the Teflon sheet on the reflection coefficient was measured using a Hewlett Packard 8410 network analyzer and standard dummy load with VSWR<1.05. Measurements showed that the reflection coefficient introduced by the Teflon sheet is less than 0.02 and its impact on the total microwave power reflected from the water taper is negligibly small.

The microwave power absorbed in water, the total power and VSWR were measured as a function of the water taper angle, α. The measurements were performed for three power settings of about 550, 750 and 890W with three water flow rates 6, 14 and 46g/s.

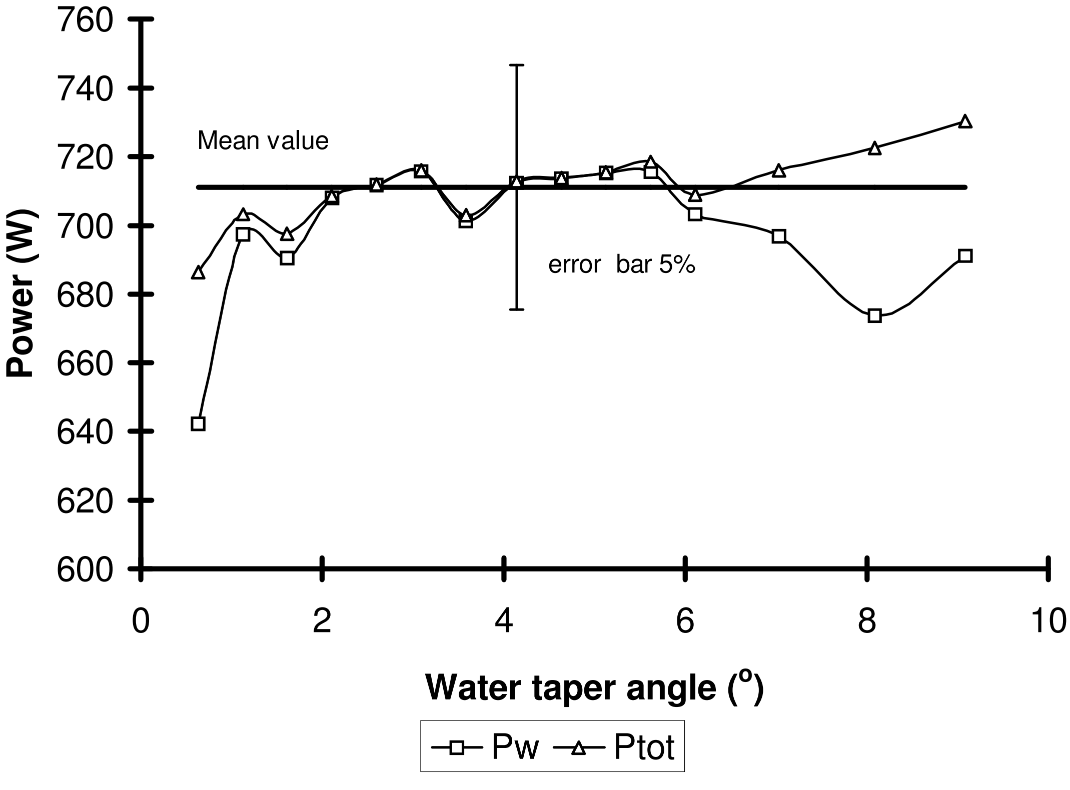

Fig. 3. Microwave power absorbed in the water taper and total microwave power as a function of the water taper angle for water flow rate 6 g/s and a power setting of 750 W.

A typical set of results for total power and power absorbed in water obtained at a water flow rate of 6 g/s and power setting of 750 W is given in figure 3. The mean value of total power calculated for the water taper angles in the range 1.6^o-7.0^o, and the error bar of ±5% are shown on this figure. The measured total microwave power is within limits of the experimental error for water taper angles in the range $1.6^o \leq \alpha \leq 7.0^o$. Outside this range a significant increase of VSWR, as shown in figure 4, leads to a decrease in accuracy.

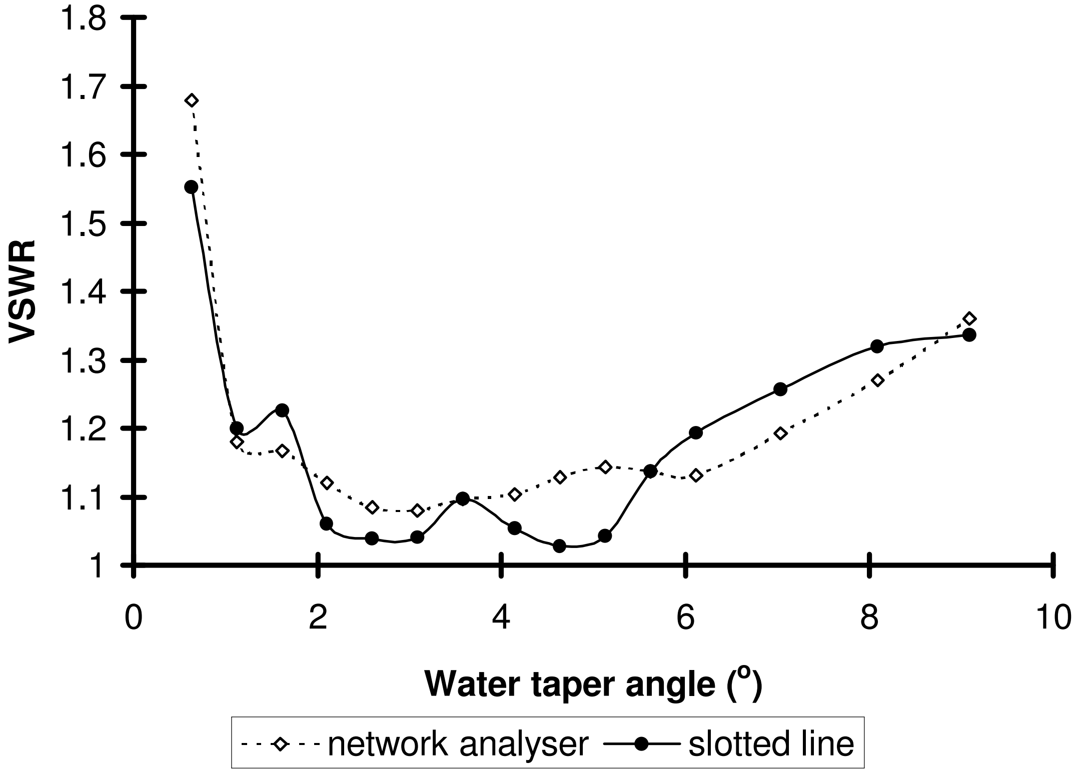

Fig. 4. VSWR measured using slotted line and network analyzer as a function of the water taper angle for water flow rate 6 g/s and a power setting of 750 W.

The accuracy of VSWR measurements using the slotted line was verified using the network analyzer. The results are presented in figure 4 as a function of water taper angle for the same conditions as in figure 3. The VSWR values obtained using the slotted line are in agreement with results obtained using the network analyzer in the range of $1.6^o \leq \alpha \leq 7.0^o$. The VSWR values increase for $\alpha<1.6^o$ due to some water flow turbulence. For $\alpha>7.0^o$, the water taper became a visible obstacle to the incident microwave radiation and cause an increase of VSWR. A small difference between the results, especially for small and big values of angle, α, is caused by inaccuracy of the slotted line.

The power absorbed in water and the total power for the flow rate of 14 g/s and power setting 550 W are shown in figure 5. For the range $1.6^o \leq \alpha \leq 7.0^o$, the mean value of total power and the error bar of ±5% are shown. The trends in this figure are similar to those in figure 3. For α in the range 1.6^o-7.0^o, the total power and the power absorbed in the water are in good agreement and within the limit of experimental error. For $\alpha<1.6^o$ or $\alpha>7.0^o$, the inaccuracy in the total power measurements significantly increases due to an increase of the VSWR values. The measurements of VSWR obtained using the slotted line and the network analyzer as a function of water taper angle are shown in figure 6. The trends are similar to whose in figure 4 and VSWR less than 1.3 was obtained for α in the range 1.6^o-7.0^o.

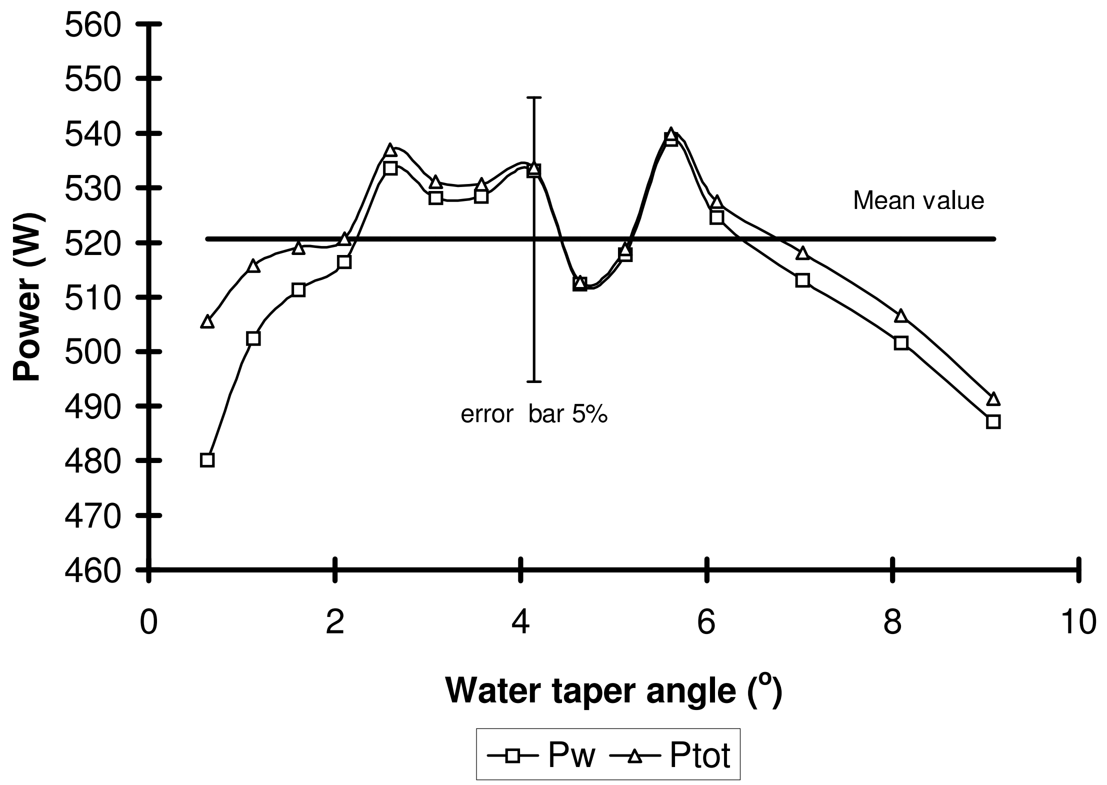

Fig. 5. Microwave power absorbed in the water taper and total microwave power as a function of the water taper angle for water flow rate 14g/s and a power setting of 550W.

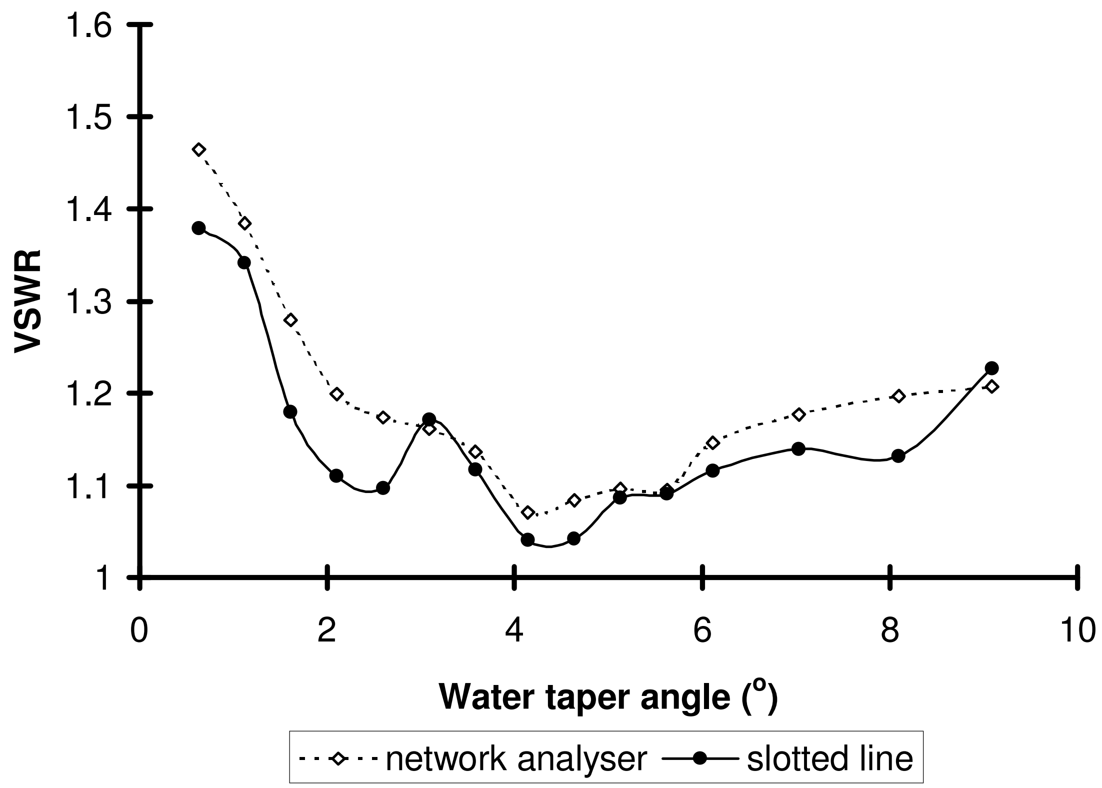

Fig. 6. VSWR measured using slotted line and network analyzer as a function of the water taper angle for water flow rate 14g/s and a power setting of 550W.

The total microwave power as a function of water taper angle, α for various water flow rates and power settings is shown in figure 7. The results of the total power calculated from the calorimetric measurements at a flow rate of 14g/s are within ±5% when compared with the power measured using the directional coupler. For the water flow rate of 6 g/s, the difference between the power obtained from the calorimetric measurements and that shown by the directional coupler is higher. This is due to an increase of heat loss to the surroundings. For flow rates, 6g/s and 14g/s, the P_{tot} remains virtually unchanged, within ±5%, for values of α in the range 1.6° to 7.0° and can be approximated by the power absorbed in water. For flow rate of 46 g/s, the difference between the calorimetric and the directional coupler results increases due to an increase in the reflection coefficient and the relative error of the temperature measurement. The increase of the reflection coefficient is caused by the ripple occurring on the surface of the water taper.

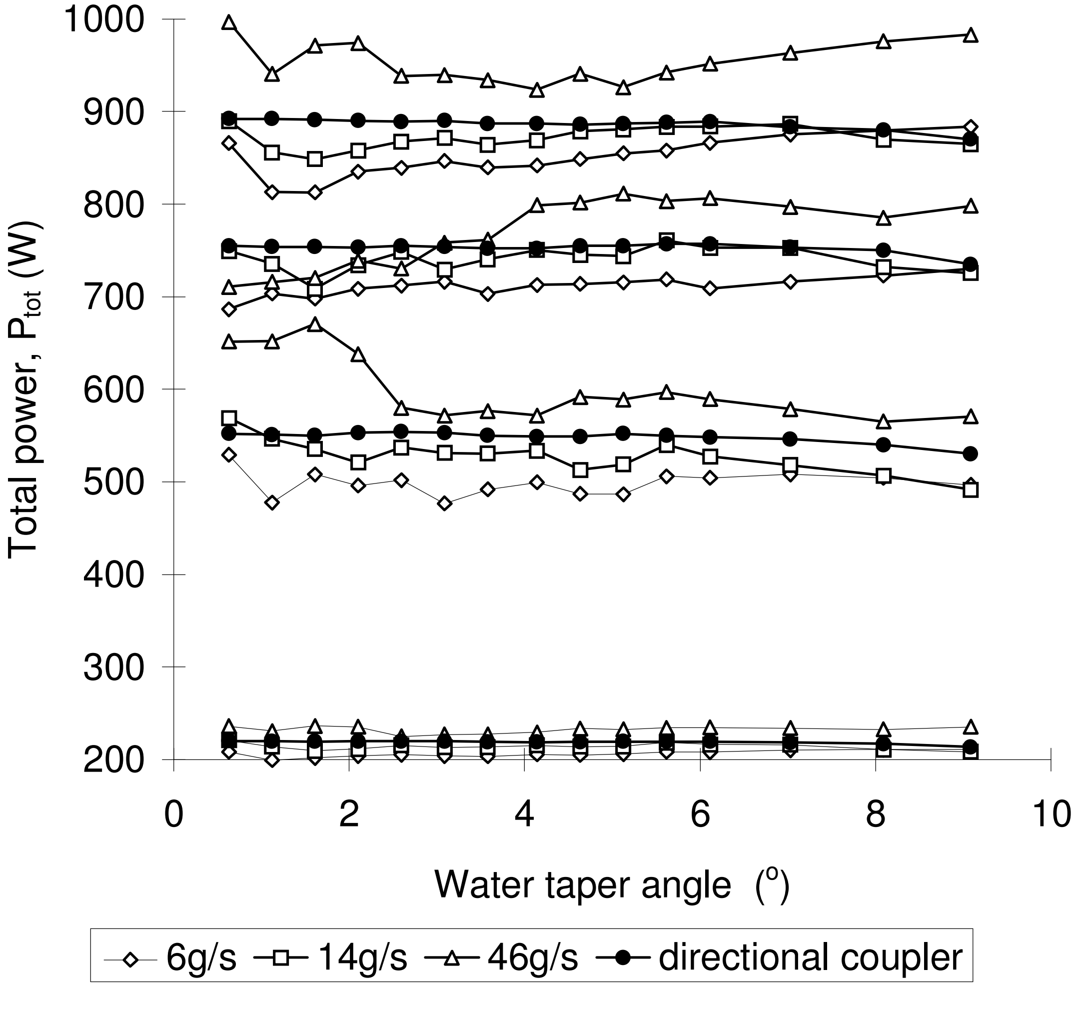

Fig. 7. Total microwave power as a function of the water taper angle for three water flow rates at various microwave power levels.

The system described above was also used for calibration of a pulse microwave power supply based on a domestic oven circuit. The measured values of the total microwave power were constant for water taper angles between 1.6^o and 7.0^o and flow rate 14g/s with a standard deviation of ±30W at a power setting of 820 W.

6. Conclusions

A simple waveguide based flow calorimeter was build and used for calibration of a high power microwave source. The microwave power transmitted in the waveguide was absorbed in the water taper. For water taper angles in the range 1.6^o-7.0^o and the flow rate of 14 g/s, the total microwave power remained constant within the limits of experimental error. The total power transmitted in the waveguide was determined with an accuracy better than ±5%.

The water flow rate has a significant impact on the accuracy of the power measurements. The water flow rate should be kept in the range at which no ripples occur on the surface of the water taper and the water temperature rise is small enough not to cause a significant increase of heat loss.

For water taper angle $1.6^o \leq \alpha \leq 7.0^o$, in which the values of VSWR remains less than 1.2, only a small fraction of the total microwave power is reflected from the water taper. Under these conditions the total microwave power can be approximated by the microwave power absorbed in water. In this range of the water taper angle, microwave power measurements can be made using a basic thermocouple temperature measuring system, electronic balance and stopwatch.

7. Acknowledgments

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8. References

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