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LATENT HEAT OF EVAPORATION OF A MICROWAVE IRRADIATED POLAR LIQUID *

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ABSTRACT

The quasi-stationary state of microwave evaporation of a polar liquid is studied experimentally. When the energy supplied by the field to the interface is larger than the heat flux exchanged with the surroundings, the rate of evaporation is then proportional to the microwave power absorbed and can be calculated simply by dividing the power by the standard value of the latent heat of evaporation.

When the field is low, the energy balance does not govern the process; the irreversibility must be taken into account.

INTRODUCTION

Microwave irradiation of the interface of a polar liquid and its vapour enhances its evaporation. When the intensity of the applied electric field is low, the vapour–liquid system tends to approach a quasi-stationary state of evaporation, for which its dynamic properties can be related to the experimental conditions controlled by the surroundings. Typical results were reported for a pure polar liquid (ethanol), which was evaporated under reduced pressure in ref. 1 and analysed in ref. 2.

Recently, Abtal et al. [3] discussed interfacial stability when the field is increased. They published photographs showing the deformation of the interface and suggested a Marangoni-like effect to justify the large rates of evaporation.

Let us recall the case of the stationary state. In ref. 1 we found a biquadratic formula which describes the dependence of the mass rate on the microwave power level, when evaporation is enhanced by microwaves.

$$v^2 = v_0^2 + \beta^2\pi^2$$

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* Presented as thesis work by P. Colin at the University of Nancy, 1981.

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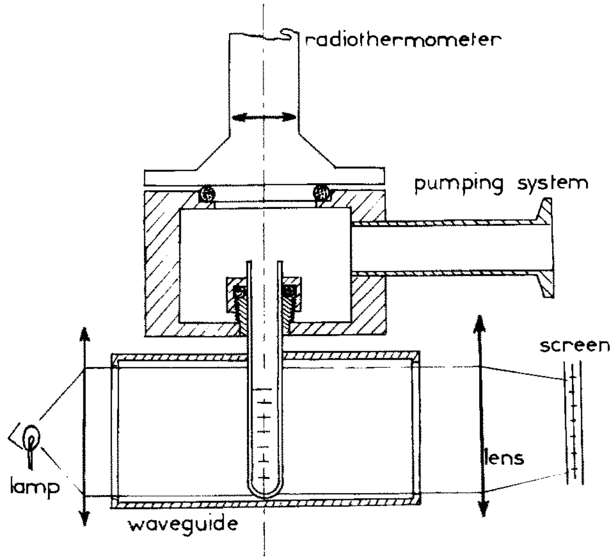

Fig. 1. Detailed view of the microwave applicator used for studying evaporation.

This formula shows a linear dependence of v versus the square of the intensity of the electric field ($E_i^2 \approx \pi$) only above a given level. It also takes into account the fact that the rate is not zero when the field is off. In the same work, the electrical field applied to the interface was estimated from the measured incident power level or from the measured absorbed power level. Only part of the liquid phase was irradiated, however, so the energy balance could not be properly evaluated because the liquid column loses heat to its surroundings.

In this paper we present new experiments, specially undertaken in order to evaluate the latent heat of evaporation of a polar liquid, when evaporation is produced by a microwave field under reduced pressure.

DESCRIPTION OF THE EXPERIMENTAL DESIGN (see Fig. 1)

The evaporating liquid fills a cylindrical tube, which is placed centrally in an RG 112/U waveguide. The open, upper end of the tube is connected to a thermostat, the temperature (T_{cp}) of which determines the pressure (P_c) of the gas as in the experiments we described in ref. 1. The cylindrical tube is closed at its lower end. The level of the evaporating surface is optically observed in the waveguide with a lamp, which projects the image of the tube onto a screen.

The microwave set-up (see Fig. 2) includes, as usual, a generator, a circulator and a means of measuring the levels of both the incident and reflected power. A short-circuit closes the end of the guide. Its position is

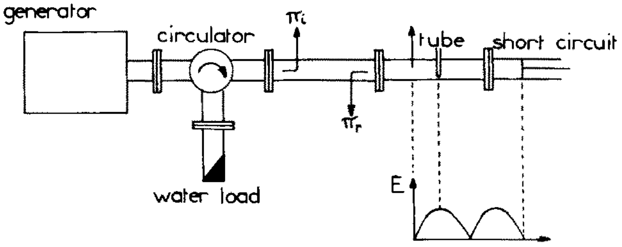

Fig. 2. Microwave set-up.

adjusted so that the stationary electric field distribution in the guide induces a maximum value at the tube. The absorbed electric power is

$$\pi_a = \pi_i - \pi_r$$

and the wave reflection coefficient is $|\rho| = (\pi_r/\pi_i)^{1/2}$. The rate of evaporation is deduced from the speed of the liquid meniscus which is projected onto a metric scale. The results we will report first do not involve temperature measurements, but are only concerned with the microwave behaviour of the system and the energy balance.

The experimental procedure is as follow: we introduce ethanol into the tube, pump out the air and carefully degas the liquid, then begin evaporation under a microwave power level, π_i, and at a fixed reduced pressure, P_c, by maintaining the temperature of the thermostat at a value T_{cp}.

While the liquid is evaporating, the volume of the liquid which is inside the guide decreases. We record curves $(h(t))$ like those shown in Fig. 3. The

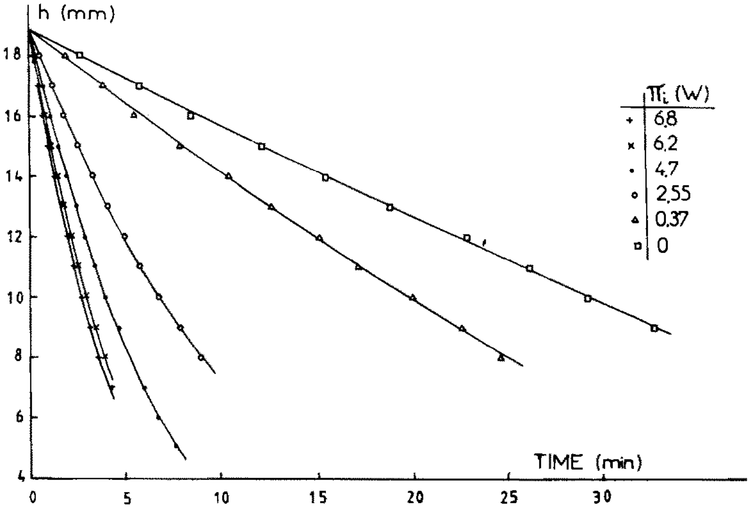

Fig. 3. Measured height of liquid as a function of time during evaporation. $T_a = 20°C$, $P_c(T_{cp}) = 12.2$ Torr.

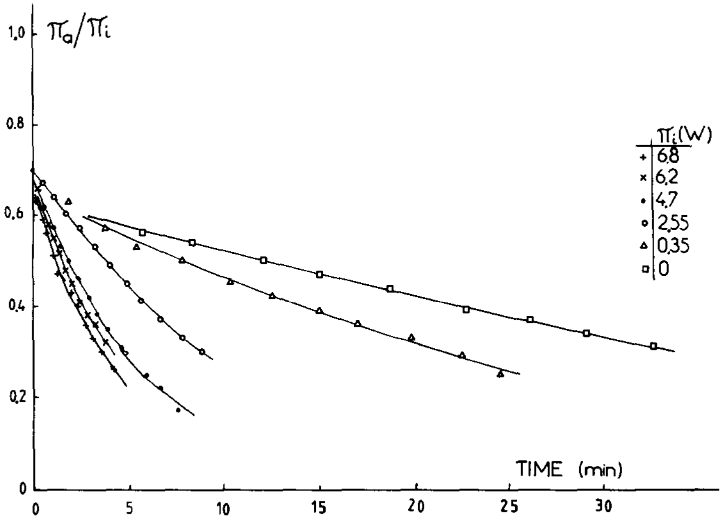

Fig. 4. Measured absorbed power as a function of time during evaporation. $T_a = 20°C$, $P_c(T_{cp}) = 12.2$ Torr.

equivalent microwave impedance that the liquid represents, and consequently the absorbed power, vary with time. Figure 4 shows typical curves of the absorbed power versus time.

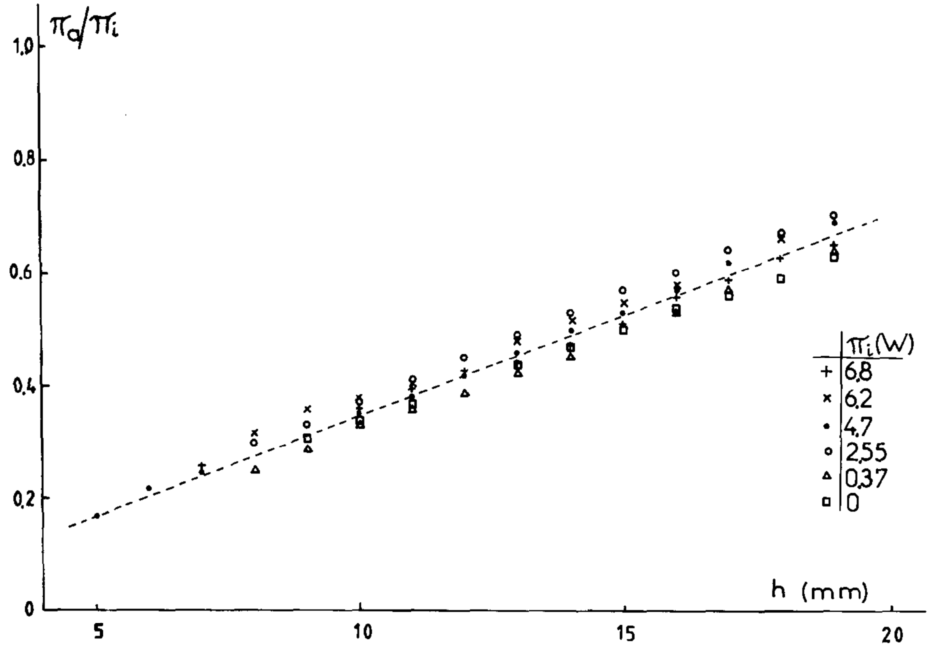

Fig. 5. Power reflection coefficient versus height of liquid.

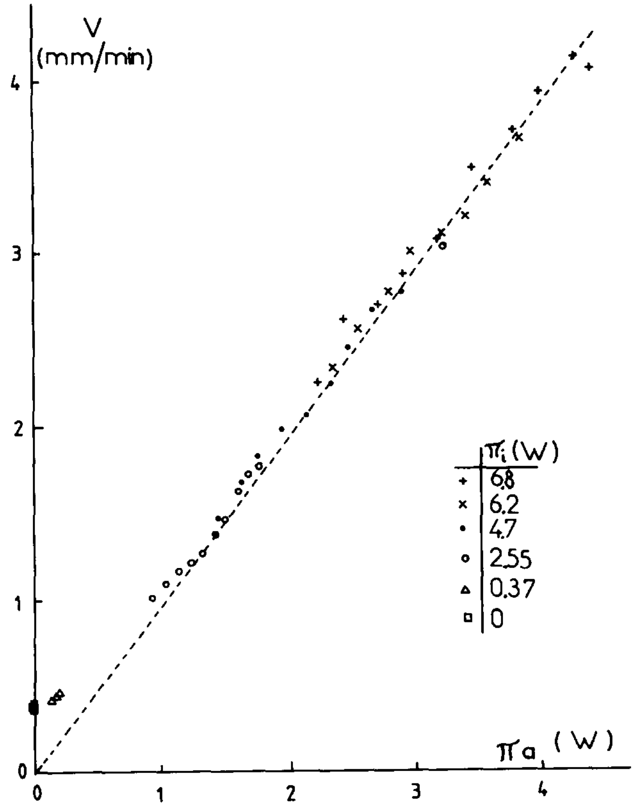

Fig. 6. Rate of evaporation versus absorbed power.

These results can be interpreted simply. First, the ratio of the absorbed power to the incident power does not depend on the rate of evaporation and, secondly, it is a linear function of the height of the liquid (Fig. 5). Thus, the field distribution is homogeneous in the liquid except perhaps near the lower and upper ends of the liquid column. The perturbation theory is probably satisfactory for describing the variation of the absorbed power as a function of the height of the liquid, because π_a is linearly dependent on the volume. The slope of the straight line is thus proportional to the imaginary part of the permittivity of the liquid.

The instantaneous rate of evaporation, which is determined by taking the derivative of the curve $h(t)$ and dividing by the surface of the liquid, is a function of the instantaneous absorbed microwave power, as shown in Fig. 6. The rate is not proportional to the absorbed power when the field is very low. We again find a formula like that given in ref. 1. The coefficient β is now the slope of the linear part of the curve.

$\beta = 0.96 \text{ mm min}^{-1} \text{ W}^{-1}$

This result means that the system uses 830 W to evaporate one gram of alcohol per second. This value corresponds approximately to the standard value of the latent heat of evaporation of ethanol.

We conclude that microwave energy is fully utilized to produce vapour, if the electric field intensity is large enough. At lower levels, when the applied electric power is of the order of the heat flux that the system exchanges by convection with its surroundings, the energy balance of the process is more difficult to verify. Microwaves probably modify the coupling of heat and mass transfers and reduce the portion of thermal energy supplied to the surface by the liquid.

The rate of evaporation is not an addition function of the energies that the system receives from the two sources. The system seems to be able to use microwave energy preferentially for producing vapour. Furthermore, better use is made of the microwave energy when the evaporating system is well thermally isolated.

CONCLUSION

When the rate of evaporation of an irradiated liquid varies linearly with the absorbed power, the slope $\dot{m}$ versus π_a is the standard value of the latent heat of vaporisation.

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