Study of low Rayleigh heaters for biomedical diagnostic tools

D. Gosselin[1,2,3,4,5]*, J. Berthier[1,2], A. Delon[1,2], D. Chaussy[3,4,5], N. Belgacem[3,4,5], G. Delapierre[1,2]

[1] Univ. Grenoble Alpes F-38000 Grenoble, France
[2]CEA, LETI, MINATEC Campus, F-38054, Grenoble, France.
[3]University Grenoble Alpes, LGP2, F-38000 Grenoble, France
[4]CNRS, LGP2, F-38000 Grenoble, France
[5]Agefpi, LGP2, F-38000 Grenoble, France

ABSTRACT

Portability and autonomy of biomedical diagnostic devices is an on-growing trend. It is recognized that low-energy heating of such portable devices is of utmost importance for molecular recognition. In this work it is shown that screen-printed microheaters relying on Joule effect constitute an interesting solution for low-energy heating.

An experimental study of the natural convection phenomena occuring with such microheaters is conducted. Because of the thinness of the supporting film, it is shown that the contribution of both the upward and downward faces have to be taken into account. In addition a relation between the Nusselt number and the Rayleigh number is derived, leading to an accurate prediction of the heating temperature (MRE<2%).

Keywords: microheater, natural convection, low Rayleigh, screen-printing, Joule effect

1 INTRODUCTION

Microfluidic is a very promising technology to improve biomedical devices and to provide diagnostic tools for the developing world [1,2]. The World Health Organization (WHO) has introduced a list of requirements that an ideal diagnostic tool for the developing world must meet [3]. It can be abbreviated with the acronym ASSURED: Affordable, Sensitive, Specific, User-friendly, Rapid and Robust, Equipment-free, Delivered. In order to comply with these criteria diagnostic toosl should be autonomous, low-cost an portable. In other words all the required functions must be integrated on the diagnostic device. The motion of fluid is usually generated by capillary forces [4,5] and the detection by naked eyes or with smartphone camera is prefered [6,7]. Amongst all the functions necessary for such type of device, heating is one of the most important. For example, it is required for DNA amplification. It is also recognized that biological processes work better at a temperature of 37°.

A widely used approach is to take advantage of Joule effect to heat up locally the device [8,9]. Although it needs a power supply, this method remains acceptable for portable devices as soon as it has a low power consumption and rely on portable pocket batteries.

A common issue for Joule microheaters is their miniaturization. Miniaturizatrion of microfluidic systems impose miniaturization of the associated heaters. Numerous studies have been published in the case of heating plates of dimensions comprised between few centimeters and meters [10 -13]. The case of microheaters is much less reported in the literature. In fact for such small heaters the caracteristic length, defined as the area/perimeter ratio, highly depends on the dimensions. A small change of the dimensions can then greatly affect the heating temperature of the microheater.

In this work, it is first shown that screen-printed microheaters can provide a fast and stable heating. Afterwards the natural convection of Joule microheaters is investigated. First the contribution of the upward and downward faces of the microheater is analyzed. It is demonstrated that the Nusselt number (Nu) of such microheaters evolves accordingly to the 1/8-power of the Rayleigh number (Ra). Knowing this relation, the prediction of the heating temperature as a function of the applied voltage can be achieved with a mean relative error (MRE) less than 2%.

2 EXPERIMENTAL SET-UP

2.1 The heaters

The heaters have been made by the screen-printing of a resistive carbon ink on a 175µm-thick PET film. Silver ink was used for the connections. The thickness of these screen-printed layers is about 10µm. A typical heating elements is depicted in Figure 1.

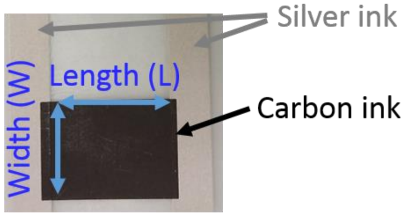

Figure 1: Formatting dimensions for manuscripts.

Microheaters with varying dimensions have been designed. The width of these devices is ranging from 11mm to 20mm and length between 5mm and 20mm.

Five elements have been used in this study to establish the relation between the Nusselt number and the Rayleigh number, Eq (8). The caracteristic length for a microheater is the ratio between the area of the plate and its perimeter:

$$L_c = \frac{A}{p} = \frac{W*L}{2*(W+L)} \quad (1)$$

These elements have been chosen to encompass a wide range of microheater shapes, i.e. a large range of L_c (see Table 1).

Element #	1	2	3	4	5
Length (mm)	5	5	12	20	20
Width (mm)	11	17	15	12	20
Lc (mm)	1.72	1.93	3.33	3.75	5

Table 1: Geometrical data of the microheaters used for the study.

Other heating devices (with other dimensions) are used to validate expression (8). The dimensions of these elements are summurized in table 2.

Element #	6	7	8	9	10
Length (mm)	5	10	15	16	15
Width (mm)	20	17	12	17.5	20
Lc (mm)	2	3.15	3.33	4.18	4.29

Table 2: Geometrical data of the heating device used to comfirm Eq (8).

2.2 Experimental set-up

During the experiments, the heating device was maintained suspended in the air (by the crocodile clips). The thermal measurments were perfomed with a ThermoVision A20 thermal camera (FLIR Systems). The power was supplied by a voltage source. Figure 2 shows the experimental set-up.

3 RESULTS AND DISCUTIONS

3.1 Transient study

In this subsection it is shown that the response of such a heating device is suitable for a biomedical diagnostic tool. In fact the heating temperature is rapidly reached. Less than 30 seconds are needed for the microheater to heat up from 25°C to 65°C (Figure 3) with a low voltage source (a few Volts). In addition this equilibrium temperature is stable over one hour (Figure 4) which can allow the run of different diagnistic tests.

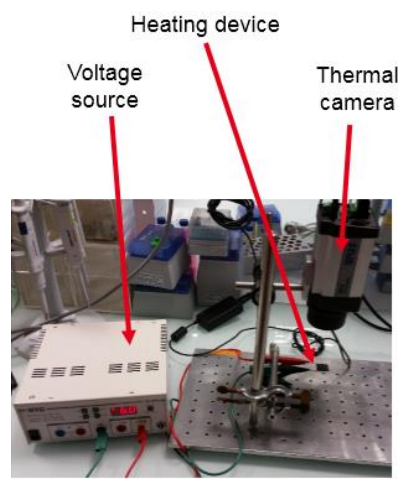

Figure 2: Experimental set-up for temperature measurement.

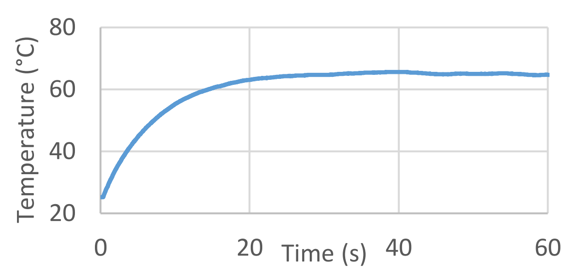

Figure 3: Dynamic of the heating up of a typical device.

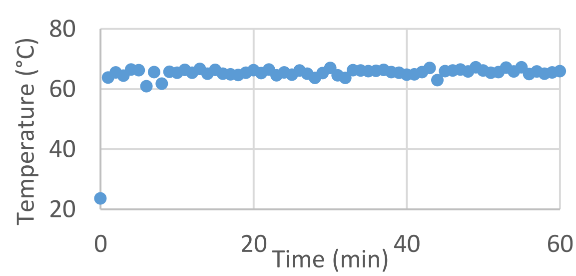

Figure 4: The screen-printed heaters are stable over an hour.

The two following sections focus on the natural convection of these microheaters. In the first section a global approach based on equations found in the litterature is used. In the second section, a local approximation based on the experimental data will be made. Besides it will be shown that the heating temperature can be accurately predicted as a function of the applied voltage.

3.2 Natural convection: Global approach

In this section, the Nusselt number is first calculated from a thin-layer aproximation (Nu^T) and afterwerads corrected into the fully laminar Nusselt number (Nu) [10]. The expressions between the Nusselt and the Rayleigh numbers do not depend of the order of magnitude of the Rayleigh number but on the geometry (flat plates, cylinder, etc) and on the orientation (vertical, horizontal, etc). For an upward-facing flat plate:

$$Nu_U^T = 0.835 \frac{0.671}{\left(1+\left({}^{0.492}/_{Pr}\right)^{9/16}\right)^{4/9}} Ra^{1/4} \quad (2)$$

where Pr is the Prandtl number, and index u for "upward".

The laminar Nusselt number is then given by

$$Nu_u = \frac{1.4}{ln\left(1+{}^{1.4}/_{Nu^T}\right)} \quad (3)$$

For a downard-facing flate plate (index D):

$$Nu_D^T = \frac{0.527}{\left(1+\left({}^{1.9}/_{Pr}\right)^{0.9}\right)^{2/9}} Ra^{1/5} \quad (4)$$

And

$$Nu_D = \frac{2.5}{ln\left(1+{}^{2.5}/_{Nu^T}\right)} \quad (5)$$

Because the heating device is screen-printed on a thin substrate and is suspended in air, natural convection occurs at the upward and downward face of the device. To model this double phenomena we define a total Nusselt number as

$$Nu = Nu_U + Nu_D \quad (6)$$

Figure 5 shows that the introduction of this total Nusselt is necessary to be in accordance with the experimental data (obtained with the microheaters described in Table 1). The downward-facing contribution is of the same order of magnitude than the upward-facing contribution and thus these two aspects have to be taken into account.

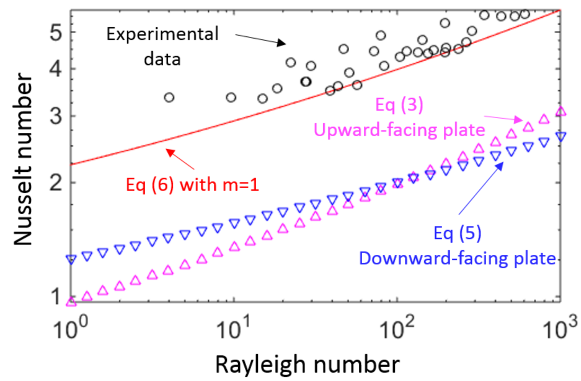

Figure 5: Comparison between experimental data (black circles) and different equations: the upward-facing equation (3) (magenta triangles), the downward-facing equation (5) (blue triangles) and the suspended equation (6) (red line)

However because of the complexity of these equations, this approach is not suited to predict the heating temperature of these devices. In the next section a local approximation of the relation between the Nusselt and the Rayleigh number is developed. This will allow an accurate prediction of the heating temperature.

3.3 Natural convection: Local approach and prediction of the heating temperature

Natural convection is often modeled by expressing the Nusselt number as a power-function of the Rayleigh number:

$$Nu = a\, Ra^n \quad (7)$$

where a and n are constant which depend on the order of magnitude of the Rayleigh number [11,12].

Figure 6 shows the fitting of Eq (7) done with the polyfit function of the MATLAB software for the five different gemetries of heaters listed in Table 1. It is found that these experimental data points can be well fitted with a 1/8-power function:

$$Nu = 2.69 * Ra^{0.124} \sim 2.69\, Ra^{1/8} \quad (8)$$

Using equation (8) allows an accurate prediction (MRE<2%) of the heating temperature of a microheater accordingly to its dimensions and to the applied voltage (Figure 7).

TechConnect Briefs 2016, TechConnect.org, ISBN 978-0-9975-1173-4

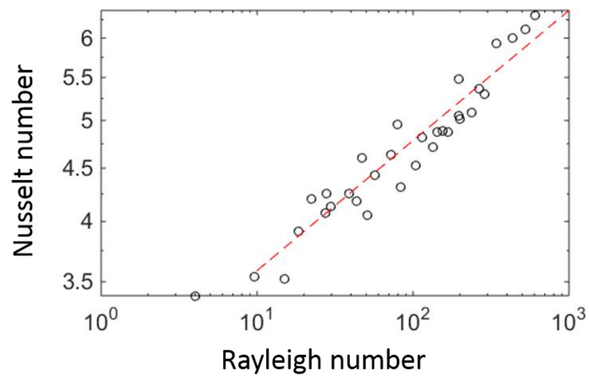

Figure 6: Black circles: Experimental data.
Red dashed line: Fit obtained with the polyfit function of MATLAB, Eq (8).

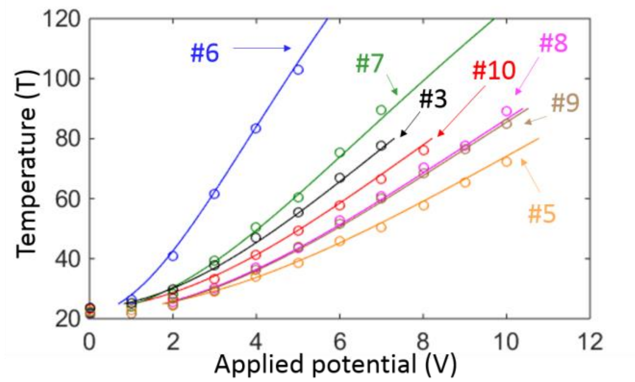

Figure 7: Comparison between prediction (solid lines) and experimental data (circles) for different heaters (labelled accordingly to table 1 and 2).

4 CONCLUSION

In this work it is shown that screen-printed microheaters relying on Joule effect can be an interesting way to integrate a heating function on a portable diagnostic tool. In fact the heating temperature is reached within 30s and is then stable over one hour allowing to perform biological analyses.

In addition the natural convection have been studied and is has been shown that, because of the thinness of the supporting film, the contribution of both the upward and downward face have to be taken into account. It has also been demonstrated that for such microheaters the Nusselt number evolves accordingly to the 1/8-power of the Rayleigh number. Finally on the basis of this relation a prediction of the heating temperature can be accurately done (MRE<2%).

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