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Milli calorimeter for a droplet flow by InfraRed Thermography

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Abstract

The aim of this paper is to propose a new thermal method devoted to the estimation of heat exchange coefficients in isoperibolic biphasic millifluidics devices. First, an experimental set up, which couples InfraRed and visible measurements of the droplets flow is presented. Then, a Lagrangian approach is apply to work in the space of each biphasic plug (by using visible measurements) in order to demonstrate that a simple two temperatures (given by IR measurements) thin body thermal model is enough consistent to represent the thermal behaviour of such complex and heterogeneous millifluidic configuration. By using an inverse processing method, it is shown that the estimation of the heat transfer coefficients is quite easy and accurate for several flow rate ratio of the two phases. Finally, a first correlation allowing the calculation of the heat exchange coefficients by the knowledge of the thermal properties and the flow rate ratio of each phase is presented.

1. Introduction

Recently, miniaturized fluidic systems have proven to be novel and important tools for online chemical analysis and process intensification. In such systems, the transport phenomena are enhanced and allow the study of chemical reactions under a wide range of configurations [1-4]. The first studies of chemical reactions were performed in straight channels in continuous flowing system. At the inlet of the channel, a simple interdiffusional mixing zone is placed, the length of this zone is mainly handled by inner diameter of the channel and the diffusion [5-6]. Then, a large quantity of studies were dedicated to characterise the physical behavior of a droplet flow [7,8,9]. Thus nowadays a wide range of physical and chemical phenomena are studied under this configuration. Here each droplet is considered as an independent reactor; in this case the homogenous mixing can be achieved faster by chaotic advection [10], but also by the hydrodynamic recirculation inside the droplet [11]. Nevertheless, the thermal characterisation of a droplet flow in millifluidic systems has not yet being studied. So, we pay particular interest to the understanding of heat transfer mechanism in such configuration, due to the fact that almost every chemical reaction, phase transitions, mixing or wetting process is accompanied by a heat exchange. In general, thermal characterisation is important and is widely used for the characterization of chemical reactions.

The developed thermal characterisation tools are mainly based on the classical calorimetry techniques for a continuous flow configuration [2,4,12,13]. In other hand, non intrusive tools for online thermal analysis have also been developed only for the continuous flow configuration [14-16]. Previous work [14, 17] has shown the reliability to estimate the temporal evolution of the heat source and the enthalpy of chemical reaction in co-flow by InfraRed Thermography (IRT) measurements. The previous IRT studies regarding a microfluidic droplet flow [17], reported important difficulties to establish a local thermal model of the system, due to the large quantity of parameters needed for a complete thermal characterisation of the flow. In the same way, IRT millifluidic calorimetry in a co-flow system [13] pointed out the importance to extend similar techniques to multiphase flow systems (i.e. droplet configuration).

Here, the flow consists in generating a periodic train of monodisperse droplets (reactive media) interposed by inert oil (continuous phase) in an isoperibolic millifluidic device. From a thermal point of view, this is a complex system of multilayered heterogeneous media with biphasic flows. Here, the flow is performed in an isoperibolic reactor. Using this experimental configuration a simple model based on thin body hypothesis is enough to represent the thermal complexity of such system.

In this study, the direct thermal modelization, is written in Lagrangian coordinates, thus, the system can be modelized as a thin body system of two temperatures (droplet and oil) with heat source inside the droplet.Then, with the thermal solution, an inverse model to estimate the heat transfer coefficients is proposed.

The transient temperature inside of each phase (droplet and oil) is given by coupling two imaging techniques, in order to monitor the experimental response to achieve the inverse processing method. So, an IR camera is used to measure the temperature field and a visible camera monitor the flow patterns. Finally, heat transfers coeffients estimation is reported for droplet flow of oil/water for several given set of flow conditions and a first correlation law is given.

2. Experimental set up

The experimental set-up (figure 1) is made of an isoperibolic millifluidic chemical reactor [14] thermally regulated by Peltier element. Inside the reactor, a droplets flow is generated by using a syringe pump and the resulting flow evolution is measured at several wavelength by both IR and visible cameras.

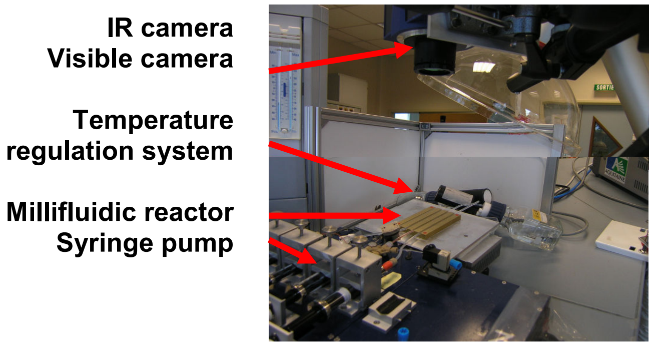


Fig. 1. *Experimental set up*

The isoperibolic millifluidic chemical reactor (figure 2.A) is made of PFA (PerFluoroAlkoxy) tubing inserted into a groove of a brass bulk. As PFA is a thin and good thermal insulator (k_t = 0.25 $W.m^{-1}.K^{-1}$) comparing to the brass bulk (k_b = 110.78 $W.m^{-1}.K^{-1}$), the boundary condition of the external diameter of the tubing is assumed to be isoperibolic. As a consequence, the temperature inside the reactor results of the heat transfer coefficient (thermal resistance) between the imposed temperature of the brass bulk (T_P) and the inner diameter of the tubing

The droplet flow is generated as shown in figure 2.B. First, the injection system of the oil (PDMS, from Sigma-Aldrich η_o = 50 and 500 mPa·s at 25°C) and the reactants is performed by high precision syringe pump (NEMESYS from Cetoni), this allows to control the flow rate (i.e. droplet generation) and the droplet size [19]. Then, the mixing starting point is controlled by using little reagents tubing. Each tube pass through a cross junction placed before the inlet of the reactor tubing. The typical dimensions of the PFA tubing are 3.17 mm for the outer diameter and 0.2 to 2.6 mm for the inner one. In this study, the inner diameter of the PFA tubing is equal to 1.6 mm. For the reagents tubing, the outer diameter is about 800 µm and the inner one is equal to 500 µm. The temperature of the metallic support is controlled by a Peltier module with PID regulation for accurate cooling and heating within the range going from -5°C to 70 °C.

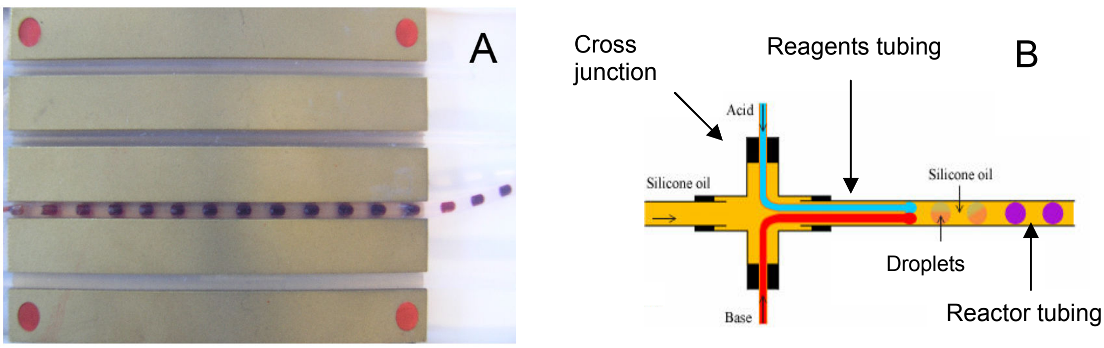


Fig.2. *A) Millifluidic reactor array. B) Layout of the reactants distribution into the droplet reactor.*

When a chemical reaction occurred in the reactor, the measurements of the flow evolution as function of time is performed by using IR and visible cameras (figure 3). An infrared CEDIP camera model JADE MWIR J550 is used for the temperature measurements of the chemical reaction whereas a visible digital camera AVT Manta GE 125 B (resolution 1296 x 964 pixels) is used to measure the flow patterns. The IR sensor is a 240 x 320 pixels InSb focal plane array with an optimum wavelength between 1.5 to 5.2 µm and a pitch of 30 µm. The IR objective lens is a 25 mm MWIR. With this objective the spatial resolution of the temperature measured by each pixel of the sensor is about 250 µm. For the visible one, the sensor is a CCD (Sony ICX445) one, the sensor size is 1/3, with optimum wavelength between 400 to 700 nm. The camera has a pitch of 4 µm, a visible objective of 16 mm (1/3 sensor size) is used, that gives a spatial resolution of 60 µm. The two cameras are triggered in order to synchronize the acquisition frame of the droplet flow.

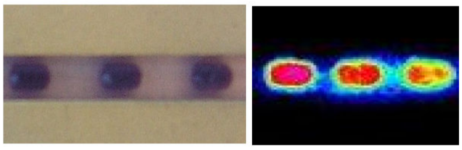


Fig.3. *Visible image (left) and IR image (right) of a droplet flow measured during the performance of a chemical reaction.*

3. Thermal modelization and inverse processing method

Such millifluidic chemical reactor can be considered as a multilayered heterogeneous media with biphasic flows, where the heat sources are due to chemical reactions with convective heat transfer between each phase. Moreover, from the thermal point of view the system can be considered as a 3D periodic established state. Whereas, from the chemical point of view, each droplet could be considered as a micro-reactor where the mixing time is controlled by the hydrodynamic recirculation [11]. As a consequence, this leads to rapidly consider the droplet as an homogeneous reactor. For all these reasons and due to the isoperibolic experimental configuration we can assumed that a simple model based on thin body hypothesis applied directly in the space of the droplet could be a first way to modelize and analyse such complex system.

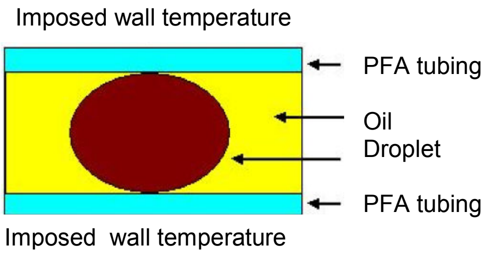


Fig.4. *Schema of the heat exchanges between the different media.*

3.1 Direct Model

The first assumption to simplify the model is to consider the periodicity of a monodisperse train of droplets. This implies that once the periodic regime is reached, the heat exchanges between the different media can be assumed as schematised on figure 4. In fact, if the temperature evolution of each droplet is quasi homogeneous, the diffusion can be neglected and the heat transfer inside the media (water or oil) can be modelized by convective heat coefficients between the droplet, the oil and also the brass bulk. We also assumed that the chemical reaction occurred only in the droplet of water. Applying image processing techniques it becomes possible to follow the average temperature evolution of each plug of oil and droplet as a function of time and also to measure the temperature of the brass bulk. Considering this local observation of each droplet and oil phases, the characteristic size of each media (oil and droplet) is close to the inner diameter (d) size of the reactor (PFA tube). Moreover, as the thermal properties of the fluids are known the Biot number (Bi) is calculated and the obtained value is lower than 1. So, in Lagrangian coordinates, the system can be modelized as a thin body system of two temperatures (droplet and oil) with heat source (due to the chemical reaction) inside the droplet, and the complete energy balance of this system can be expressed as follow:

$$\frac{dT_G}{dt} = \Phi - H_1(T_G - T_P) - H_2(T_G - T_H) \tag{1}$$

$$\frac{dT_H}{dt} = -H_3(T_H - T_P) - H_{2p}(T_H - T_G) \tag{2}$$

Where the coefficients *H* are defined as the inverse of a characteristic time (s^{-1}), and are expressed as follow:

$$H_1 = \frac{h_{GP}S_{GP}}{\rho Cp_G V_G};\quad H_2 = \frac{2h_{GH}S_{GH}}{\rho Cp_G V_G};\quad H_3 = \frac{h_{HP}S_{HP}}{\rho Cp_H V_H};\quad H_{2p} = \frac{2h_{HG}S_{HG}}{\rho Cp_H V_H};\quad \Phi = \frac{\phi}{\rho Cp_G V_G} \tag{3}$$

The system described by equation (1) and (2) can be solved by using a Laplace transform, the expressions are shown in Eqs. (5) and (6). Then, a numerical Laplace inversion on time domain (*t)* is performed by using the Den Iseger algorithm [18]. The analytical solution of the system provides the possibility to create synthetics cases, but also to perform a sensitivity analysis to study the transient thermal behavior of the two media as a function of heat exchange coefficients. The sensitivity study is also a way to enhance the accuracy of the heat transfer coefficients (H) estimation, by predicting the best experimental conditions (analysis not shown here).

$$\theta_i = \int_0^t T_i\, e^{-pt} dt \tag{4}$$

At the Eq. 4, *i* represents the integrated temperature in Laplace space for the droplet (θ_G) or the plug of oil (θ_H). Due to the isoperibolic condition, the temperature of the wall (θ_P) is kept constant.

$$\theta_G = \frac{(H_1\theta_p(p) + T_{G0})(p + H_3 + H_{2p}) + (H_3\theta_p(p) + T_{H0})H_2}{(p + H_1 + H_2)(p + H_3 + H_{2p}) - H_2 H_{2p}} \tag{5}$$

$$\theta_H = \frac{(H_3\theta_p(p) + T_{H0})(p + H_1 + H_2) + (H_1\theta_p(p) + T_{G0})H_{2p}}{(p + H_1 + H_2)(p + H_3 + H_{2p}) - H_2 H_{2p}} \tag{6}$$

3.2. Inverse Model

The final goal of our study is the estimation of kinetic and enthalpy of chemical reactions (i.e. heat source) in such droplet flow. For that, it is necessary to perform a first experimental calibration procedure of heat exchanges coefficients, in order to achieve the heat source (Φ) estimation. First, the estimation of the heat transfer coefficients (H) between the two media is done without the contribution of any heat source (no chemical reaction, Φ=0), then, by the knowledge of the thermal behaviour of the system the heat source can be calculated. Here, the inverse processing method developed for the estimation of the heat coefficient is presented. As the chemical reactions are mostly performed using diluted solutions, we can assume that the thermal properties of the chemical reactants are the same as pure water. The inverse method proposed here assumed that the averaged temperatures as function of time are measured from both media (water and oil, see experimental part). The principle is presented by Eq. 7 for the water, but the method is exactly the same for the oil. The main idea is to integrate the Eq.1 as a function of time and written a matrix form, in order to estimate the four parameters:

$$\begin{bmatrix} T_{G(1)} \\ . \\ . \\ . \\ T_{G(N)} \end{bmatrix} = \begin{bmatrix} 1 & \int_0^{t_k} T_G dt & \int_0^{t_k} T_H dt & t_1 \\ . & . & . & . \\ . & . & . & . \\ 1 & \int_0^{t_N} T_G dt & \int_0^{t_N} T_H dt & t_N \end{bmatrix} \begin{bmatrix} T_{G0} \\ (H_1 + H_2) \\ -H_2 \\ -H_1 T_p \end{bmatrix} \tag{7}$$

Where t_k is the experiment time, k=[1:N]. N is the base of time of the measurement. The Eq. 7 is written under the general linear form Y=X·P, where P is the parameters vector to estimate, X represents the sensitivity matrix of the experimental measures and Y is the observable of the system, that means the most noisy data. Eq. 2 can also be expressed with the same general form. The Gauss Markov method [20] is used to perform the parameter estimation by solving the least square problem (Eq. 8) :

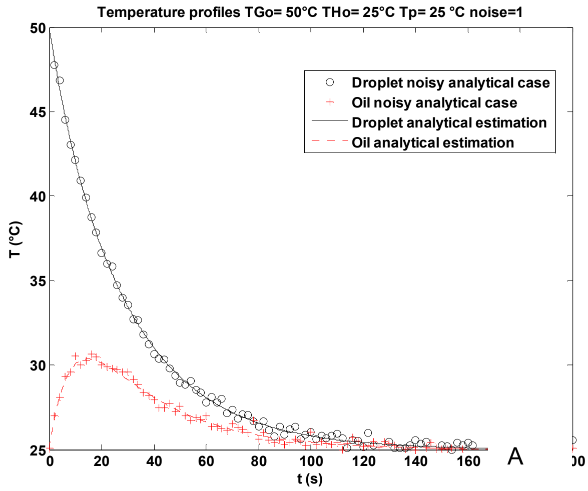
$$P = \left({}^{T}[X][X]\right)^{-1} \cdot {}^{T}[X]Y \tag{8}$$

From the estimated parameters P, each heat transfer coefficients (H) can be calculated as well as the initial temperature of each media (T_H and T_G) as well as the imposed temperature of the wall (T_P). In order to test the influence of the noise induced by the temperature measurement uncertainties on the inverse method, a synthetic case (see figure 5A) with several Signal and Noise Ratio (SNR) is generated with the developed analytical solution (Eqs. 5 and 6). The results obtained for different SNR and the related parameters estimations errors are summarized on table 1.

Table 1. *Relative error on the H coefficients estimation and the absolute error made on the temperature.*

Case	σ	H1	H2	H2p	H3	TG	TH	TP	SRN
		%	%	%	%	K	K	K	
A	0.05	0.1102	0.422	0.0355	0.0229	0.0022	0.0017	3.717×10^{-5}	125
B	0.3	0.7626	2.7384	0.2745	0.2757	0.0119	0.0121	$5.447 \times 10\text{-}^{4}$	20.83
C	1	1.1074	2.8836	0.5459	1.1981	0.0020	0.0045	0.0035	6.25

As seen in Table 1, three levels of noise are analysed (gaussian variance σ). We observed that the precision of the estimation decrease when the level of noise increase. Nevertheless, even for an important SNR of 6.25 comparing to the one given by IR camera (SNR=100), a small estimation error on the H coefficients (<3%) and on the initial temperatures (< 10^{-2}) are obtained. This case is represented as an example on figure 5. It is shown (figure 5B), that the relative residues calculated as follows: $\varepsilon = (T_{model}\text{-}T_{exp}/T_{model})*100)$ is in good agreement with the SNR introduced in the analytical solution. In fact the value of the error is equal to 3%, this corresponds to 3σ.



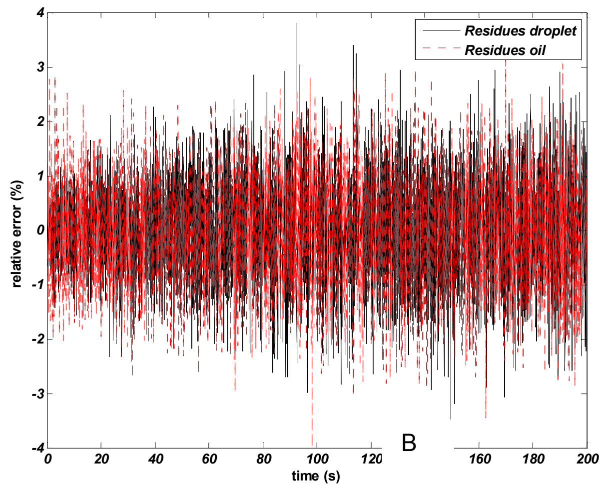


Fig. 5 *A) Comparison between generated and noised analytical solution (dash curve) for oil and water and estimated temperatures (solid line) with the inverse method. B) Calculated Relative error between generated and estimated temperatures.*

Finally, a weak influence of the noise was observed over the H coefficient estimation. We confirm the robust behavior of the proposed inverse model after the evaluation at different noise levels.

4. Experimental results

4.1 Temperature profile extractions

To achieve the estimation of the heat exchange coefficients, it is necessary to develop the image processing method devoted to the change of space from the periodic measured data to the transient local space of the plugs. In fact, the data obtained with both IR and visible cameras are represented on figure 6. The first image (figure 6A) corresponds to the visible measurement performed at one time t. The second one (figure 6B) represented the image measured in the IR domain at the same time. The third one (figure 6C), is the IR image when the averaged value of the thermal established state is subtracted.

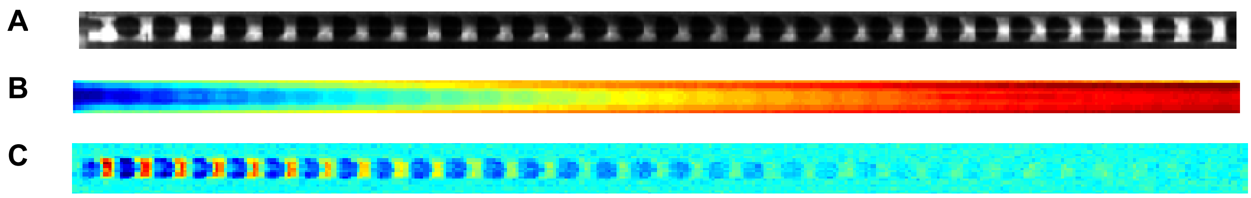


Fig.6. *Droplet flow seen by: A) Visible camera, B) Infrared thermography, C) Temperature field processing, based on the average thermal image in the axis direction.*

From this measured periodic data it is necessary to extract the averaged temperature of oil and water as a function of time to realise the inverse processing method. For that, the x direction averaged value (performed along y direction) of each images are plotted as function of time for the IR one (figure 7 A) and visible one (Figure 7B). From these representations and thanks to a least square method the average velocity and the size of the plug can be estimated.

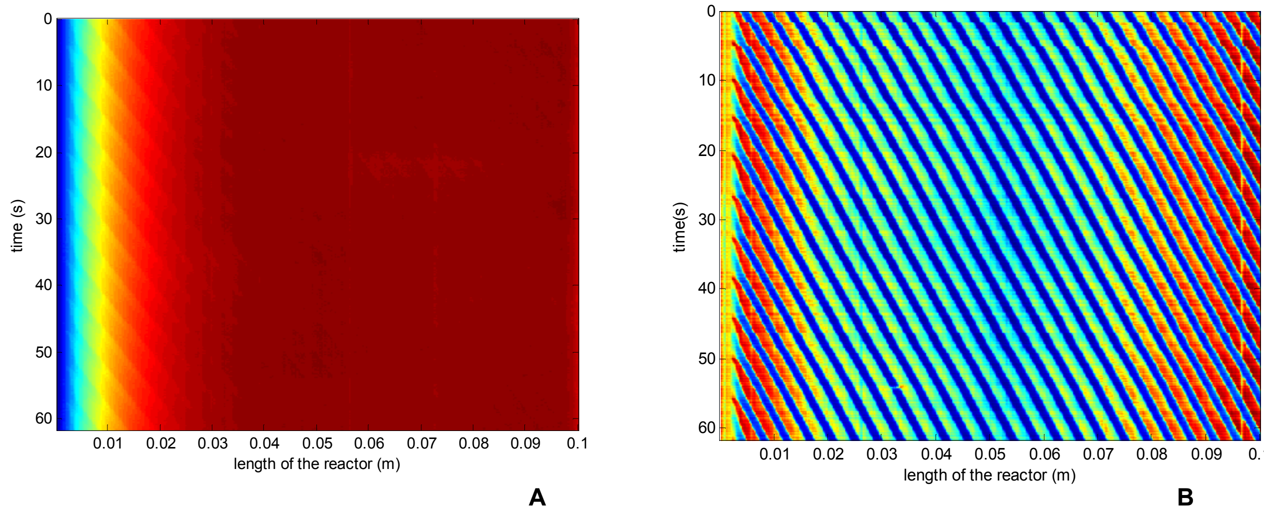


Fig.7.*A Temperature cartography giving the temperature profiles as a function of space and time for one given set of flow conditions. Each line corresponds to a temperature profile and the map evidences the drops trajectories. B. Flow patterns and droplets trajectories can be precisely observed by using a visible camera.*

The very important point in this problem is to use visible images to precisely detect the velocity and the sizes of the droplets. In fact, as it is shown on the figure 6B the digital level of the temperature evolution of each pixel along the channel is strongly influenced by the thermal homogenization through the PFA tubing. Whereas, the digital level of the same flow measured by visible camera (figure 7B) gives a better contrast and spatial resolution. The idea here is to use the visible images to perfectly detect the edge of the two plugs, in order to determine the averaged velocities of the droplets and the size of each plug. Then, a mask is adjusted with the knowledge of the optical magnitude between IR and visible. This change of scale is applied on the IR measurement to ensure that the averaged temperatures of each plug are calculated with the real (visible one) size in order to avoid any influence of the diffusion process. All these image processing allow us to obtain the temperature evolution as a function of time as is shown on figure 8.

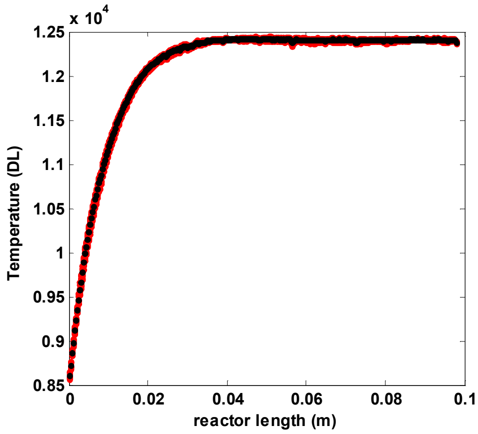


Fig. 8. *Temperature profile along the channel of one droplet (red dots). The temperature profile is tracked for all the observed droplets, from this measures a mean temperature profile is calculated (black dots). The same image analysis is done for the oil phase.*

4.2 Experimental validation on water/oil droplet flow

In order to validate the proposed thermal model and the inverse method, the following experimental configurations were performed. The experimental conditions of the measure are summarized in table 2.

Table 2. *Experimental conditions for the estimation of H coefficients.*

Q_G	Q_H	Q_{Total}	Ratio	T_{G0}	T_{H0}	T_P	pCp_G	pCp_H
$ml.h^{-1}$	$ml.h^{-1}$	$ml.h^{-1}$	Q_H/Q_G	°C	°C	°C	$J.m^{-3}.K^{-1}$	$J.m^{-3}.K^{-1}$
2	6	8	3	22	22	51.5	$4.18x10^6$	$1.26x10^6$
2	8	10	4	22	22	51.5	$4.18x10^6$	$1.26x10^6$
2	10	12	5	22	22	51.5	$4.18x10^6$	$1.26x10^6$

In fact, these cases are very interesting, they were chosen thanks to sensitivity analysis. Here, the same fluids are used for the all the experiments so that ratio between mass density and specific heat of water is kept constant (i.e. pCp_H/ pCp_G), the ratios between the fluid flow were modified from 3 to 5 (i.e. Q_H/Q_G).The values of the estimated H coefficients are presented in table 3. Only the second case of ratio = 4 is shown in figure 9, where, the experimental and theoretical profile are plotted in figure 9A and the resulting relative error < 0.3% is plotted in figure 9B which seams to be.

Table 3. *Experimental estimation of H coefficients.*

Ratio	**H1**	**H2**	**H2p**	**H3**
Q_H/Q_G	s^{-1}	s^{-1}	s^{-1}	s^{-1}
3	0.150	0.912	1.01	0.142
4	0.197	4.22	4.00	0.197
5	0.241	0.618	0.387	0.239

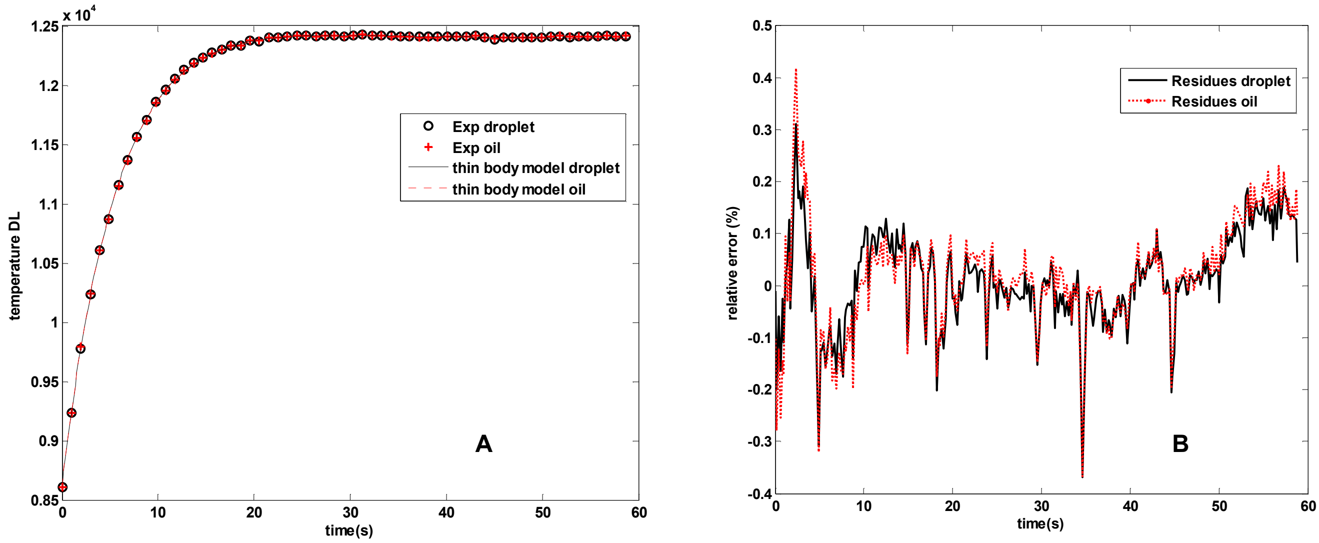


Fig. 9. *A) Experimental temperature profiles of droplet and oil are represented as 'o' and '+' respectively. Where this experimental profiles are used to estimate H coefficients. Then the estimated coefficients are applied to the thin body model to estimate the analytical temperature profile plotted as full and dotted lines respectively. B) The relative error is plotted as percentage.*

The results are very interesting especially the comparison of the estimated coefficients. In fact, we know that the total flow rate is constant due to the mass conservation principle and can be written as $Q_{Total}=Q_H+Q_G$. Then, the flow expressions can be rewritten according to ratio of the flow rates (i.e. $Q_H=3Q_G$ for the ratio of 3). Then, we assumed that the inner section of the channel is constant and also that this inner section impose the diameters of the plugs of water and oil.

If we consider that both, droplet and oil have a cylinder form of same diameter. The relation of the heat exchange coefficients between the oil/plate and the droplet/plate can be estimated from the ratio between H1 and H3 as follow:

$$\frac{H_1}{H_3} = \frac{h_{GP}\rho Cp_H}{h_{HP}\rho Cp_G} \tag{9}$$

Equation 9 clearly shows that the estimation of the heat transfers coefficient (h_{GP} and h_{HP}) through the relation H_1/H_3 is independent of the imposed flow rate ratio and rather related to the thermo physical properties of the involved media. In order to understand the behavior a well known correlation is used. It is based on dimensionless numbers for a laminar flow such as $Nu=1.64(Re\cdot Pr\cdot D/L)^{2/3}$ and it is applied for each phase as Nu_G/Nu_H. Then, after developpement and rearrangement we found that H_1/H_3 is a constant proportional to the ratio between diffusivities of both media $(\alpha_G/\alpha_H)^{2/3}$ (where $\alpha=\lambda/\rho C_p$). In our case, for the given set of fluids and flows we know that this ratio is equal to 0.93.

Also, as it was previously explained the oil phase is inert and is used as a spacer between each reactor (droplet) and the thermo physical properties such as α_H of the oil are well characterised by the supplier. So, it is possible to estimate the properties of the droplet media (ρC_p).

Whereas, the relation between H_2 and H_{2p} (Eq. 10) concerns the oil/droplet and the droplet/oil exchanges. Here, we consider the same heat exchange surface between both phases, and we make the assumption that the heat transfer coefficient between oil and droplet ($h_{GH}=h_{HG}$) is the same. Thus, Equation 10 shows a strong relation between the heat transfer coefficient and the imposed flow rate ratio (see table 2) for a given set of fluids.

$$\frac{H_2}{H_{2p}} = \frac{\rho Cp_H Q_H}{\rho Cp_G Q_G} \tag{10}$$

Table 4. *Analysis of the relation H_1/H_3 described by equation 9.*

Ratio	**H_1/H_3**	**$\rho Cp_G / \rho Cp_H$**	**Relative error %**
Q_H/Q_G			
3	1,056	3.31	11,4449987
4	1	3.31	6,48591861
5	1,008	3.31	7,22809386

At table 4, we notice that relation H_1 versus H_3 (Eq.9) for all the ratio is a constant close to 1 and ρCp is kept constant. We confirm through the experimental results and a simple correlation that the heat exchange coefficients h_{GP} (droplet/plate) or h_{HP} (oil/plate) are independent of the flow rate ratios and only depend on the physical proprieties of the fluids. The resulting relative error between the correlation value (0.93) and the experimental one (1) is around 6-11%. The estimated relative error is weak, so maybe this correlation is not well adapted for laminar diphasic flows.

The results prove that the estimations are quite realistic comparing to the physical and thermal predicted behaviour. The results validate our method, and show that for further experiments H_1 and H_3 have to be calibrated only once for each set of fluids, for example if we use a different oil.

The results summarized in table 5 concern the relation expressed by Eq.10. Here we notice the strong relation between the H_2/H_{2P} and the impose flow rate ratio. We also observed that at some flow rate ratio H_2/H_{2P} is close to unity so it is proportional to the thermo physical properties ratio of the fluids. At this condition, we are able to estimate the pC_p of the droplet.

Table 5. *Analysis of the relation H_2/H_{2P} described by equation 10.*

Ratio	**H_2/H_{2P}**	**$\rho Cp_G/\rho Cp_H$**
Q_H/Q_G		
3	0,903	3.31
4	1,055	3.31
5	1,596	3.31

5. Conclusion

An experimental set up based on visible imaging techniques allows to monitor the droplet flow but also to achieve the precisely detection of the droplet and the oil edges. Then, the superposition between the visible detected phases and IR measurements allow to extract the transient temperature evolution of each phase. The proposed inverse model for a simple model based on a thin body system of two temperatures achieves the estimation of heat transfer coefficients in diphasic media under flow. The obtained results prove that the isperibolic configuration of the system is in good agreement with the proposed simplified model. The first correlation law shows the heat exchanges between both phase (i.e. droplet and oil) are linked to the imposed flow rate ratios (Q_H/Q_G), while the heat exchanges between each phase and the plate are rather sensitive to the thermo physical properties of the fluids. Besides, it is also possible to estimate the thermo physical properties (ρC_p) of the liquids inside the droplet.

Thereafter, a wide range of experiments would be performed at different flow rates and ratio between the two phases in order to propose a formal correlation. Then, by the knowledge of the thermal behaviour, a chemical reaction will be characterized to accomplish the estimation of a heat source and the kinetic.

Nomenclature

Cp	Specific heat $J.kg^{-1}.K^{-1}$	p	Laplace variable
h	Heat transfer coefficient, $W.m^{-2}.K^{-1}$	d	Diameter, m
S	Exchange surface, m^2	Q	Flow rate $ml.h^{-1}$
V	Volume, m^3		
T	Temperature, K	Greek Symbols	
TG0	Initial temperature of the droplet, K	ρ	Density, $kg.m^{-3}$
TH0	Initial temperature of the oil, K	Φ	Heat source, $K.s^{-1}$
L	Length, m	λ	Conductivity, $W.m^{-1}.K^{-1}$
t	Time, s	θ	Laplace temperature, K

μ Viscosity, Pa.s
β Global heat transfer coefficient s^{-1}

Indices et exponents
G Droplet
H Oil
P Plate wall

1 Exchange between droplet and wall
2 Exchange between droplet and oil
2p Exchange between oil and droplet
3 Exchange between oil and wall

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