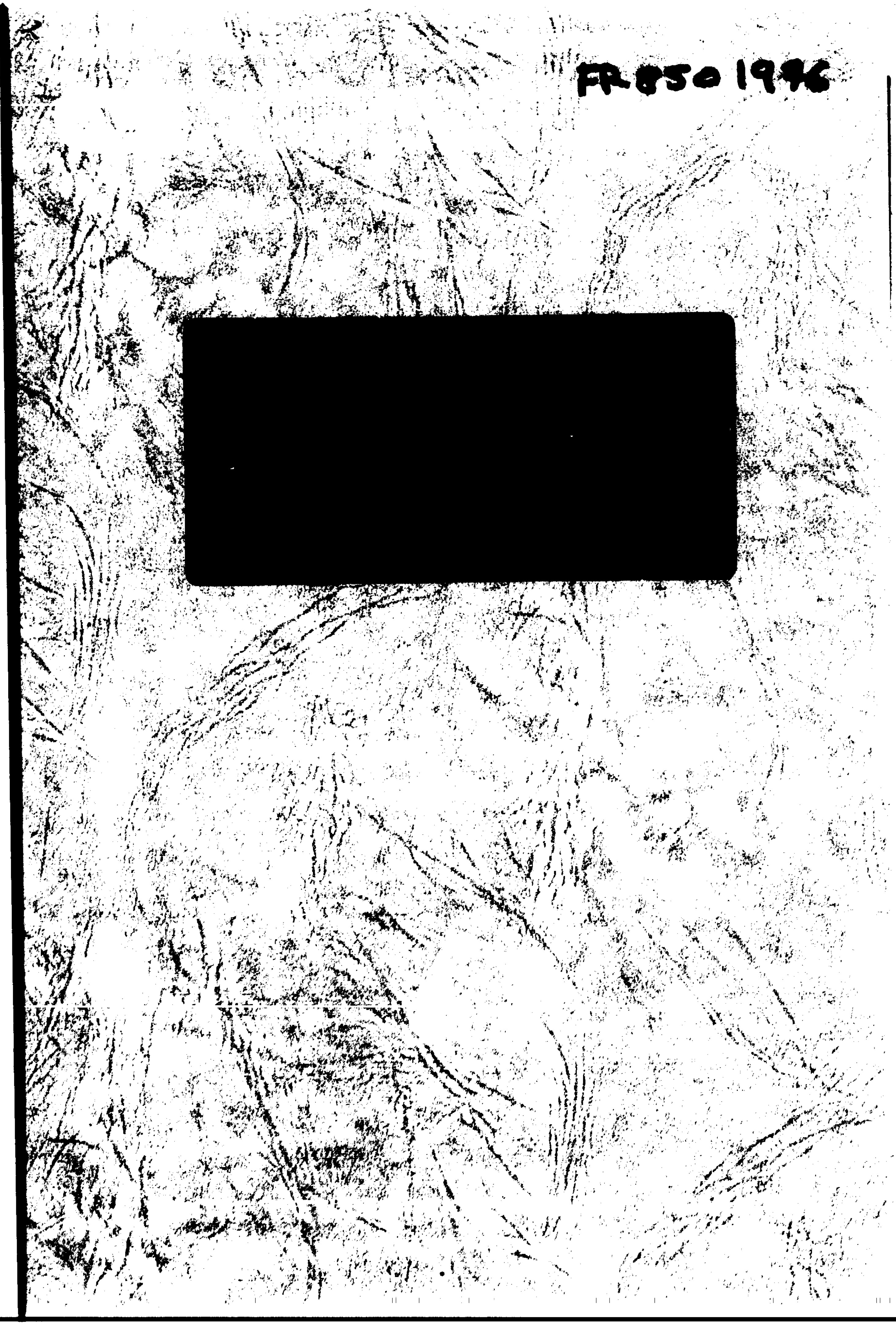

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# TEMPERATURE DISTRIBUTION IN THE REACTIVE JET OF WATER VAPOR AND LIQUID SODIUM - CONTRIBUTION TO WASTAGE MODELLING

Francis ROGER, Kwon Young PARK, Jean-Louis CARREAU,
Laurent GBAHOUE, Philippe HOBBES

## RESUME :

The possibility of water vapor leaks across the wall of one or more of the heat exchanger tubes in the steam generator constitutes one of the important problems of safety of the Fast Breeder Reactors cooled by sodium. The jet thus formed can, in fact, destroy the neighbouring tubes. The hydrodynamic, chemical and thermal factors play an important role in this phenomenon and only the last-mentionned will be studied here.

The use of the integral method of analysis, complemented by an experimental study, shows that the temperature profiles are Gaussian ; if the maximum temperature is less than that of the boiling point of sodium, i.e. 1155 K, an equation of the type :

$$\frac{c_i \, DT_c}{H_o} = \left( \frac{x}{do} \right)^{-1.1} \left( \frac{\rho_\infty}{c_o} \right)^{-0.6} Re_o^{1.5}$$

accounts satisfactorily for the thermal factor of the phenomenon.

UNIVERSITE DE POITIERS - G.R.C.P.C. - Domaine de Deffend
MIGNALOUX BEAUVOIR - 86800 SAINT JULIEN L'ARS

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## ABSTRACT

The possibility of water vapor leaks across the wall of one or more of the heat exchanger tubes in the steam generator constitutes one of the important problems of safety of the Fast Breeder Reactors cooled by sodium. The jet thus formed can, in fact, destroy the neighbouring tubes. The hydrodynamic, chemical and thermal factors play an important role in this phenomenon and only the last-mentionned will be studied here.

The use of the integral method of analysis, complemented by an experimental study, shows that the temperature profiles are Gaussian; if the maximum temperature is less than that of the boiling point of sodium, i.e. 1155 K, an equation of the type:

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accounts satisfactorily for the thermal factor of the phenomenon.

## LITERATURE SURVEY

The progress realized since many years in the production of nuclear energy has led to the use of liquid metals as the heat transfer fluid in steam generators.

In fact, the existence of high temperatures of the order of 750 K precludes the use of pressurized water. As for the molten salts, they are corrosive. The use of a gas, for the heat transfer, necessitates very high service pressures. Sodium, the only liquid metal used practically, possesses some interesting physical properties like high thermal conductivity, low melting point and low viscosity, but it is highly reactive with steam.

In the steam generators, sodium at high temperature circulates around incoloy tubes carrying steam at high pressure. Any leak of steam from these tubes of wall thickness 2.6 mm (1) results in the formation of a reactive jet of steam in sodium. The jet thus formed attacks surrounding tubes and can cause significant damage to the steam generator. This phenomenon is called wastage.

The mechanism of wastage is not yet well understood. As pointed out by TREGONNING et al. (2), it can neither be represented by a simple model of the erosive action of the jet nor by a simple model of corrosion by the products of the sodium-water reaction.

A few theoretical studies of wastage (3), (4), (5) and a lot of empirical equations for modelling wastage are already available in the literature. According to CHAMBERLAIN et al. (6), the mass flow rate of steam $m_o$ ($kgs^{-1}$), the distance between the injector and the target tube x (m), the temperature of sodium TNa (K) and the alloy composition of the target are the essential parameters governing wastage. For example, with $d_o$ (m), defined as the leak hole diameter and for the value of the $x/d_o$ between 25 and 150, HORI (1), has proposed the following empirical formula for the wastage rate, based on the wastage data obtained world-wide for the 21/4Cr - 1Mo steel alloy :

$$w = \frac{4\ 10^{-3}}{x} \exp\left(-(0.1(\ln 42\ m_o)^2 - \frac{5500}{T_{Na}}\right) \quad (1)$$

where w is the wastage rate in (ms ). The graph of the function is presented in figure 1 :

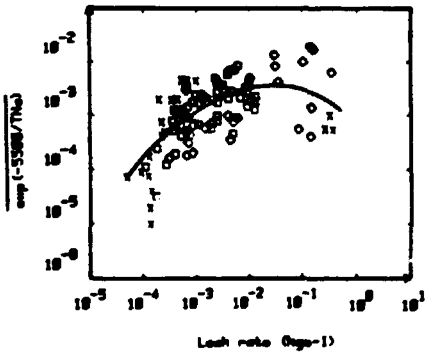


Figure 1 : Synthesis of the global data on wastage (1)

For lower values of $x/d_o$, the equation (1) is not verified and w decreases with $x/d_o$. Also the form of the impact on the targets evolves as a function of $r_o$ or x. This evolution of the affected zone is well described by KANEGAE et al. (7) and it seems necessary to analyze the hydrodynamic, thermal and chemical aspects of the reactive jet of steam in sodium to arrive at a better understanding of wastage.

From the point of view of chemistry, the steam reacts with sodium and produces sodium hydroxide and hydrogen according to the following global reaction :

$$H_2O_{(g)} + Na_{(l)} \longrightarrow NaOH_{(l)} + \frac{1}{2} H_{2(g)} \quad (2)$$

According to PARK (8), the jet can be divided into four zones (figure 2) :

- an expansion zone (I) where the steam escaping through the leak orifice, expands to the external pressure. The length of the expansion zone is very small (probably of the order of 2 $d_o$)
- a potential core (II) where the steam conserves its initial speed $u_o$ ($ms^{-1}$). Various values for the length of this zone have been cited in the literature and probably is between 6.5 $d_o$ (9) and 10 $d_o$ (10)

- a reaction zone with sodium (III) : this zone of small length is characterized by a high temperature, superior to that of vaporization of sodium

- a zone where the jet cools down (IV) due to the supply of fresh and cooler entrained sodium.

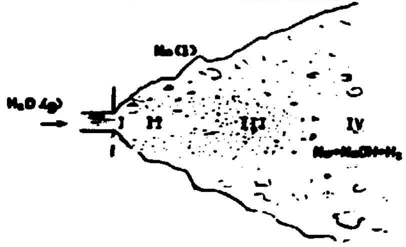


Figure 2 : Description of the reactive jet (8)

According to TREGONNING (4) the axial temperature of jet has a preponderant influence on the wastage and we will develop this point here precisely.

The combustion in the submerged turbulent reactive jets in liquid metals has till now not been sufficiently studied. Most of the existing work is oriented towards the homogeneous phase and the influence of the difference of density between the jet and the surrounding fluid needs to be examined. The experimental determination of the distribution of temperature in the interior of the jet, as also the correlation of these results with an integral model shall constitute the fundamental objectives of this presentation.

## MODELLING BY THE INTEGRAL METHOD

According to TAMANINI (11), the integral method of analysis is well-adapted for the study of the submerged reactive jets and has already been utilized frequently in the study of mono-phase (12) and two-phase systems (13). The integral method does not lead to a point wise description of the flow-field governed by the differential equations of conservation of mass, species, energy or momentum, but it does furnish global information on the evolution of the temperature profiles as a function of x or $\rho_o$.

In the analysis that follows, we make the following simplifying assumptions :

1) The jet is in steady state
2) The reactive flow is frozen and the jet essentially consists of liquid sodium and an aerosol of hydrogen and sodium hydroxide.
3) The influence of the chemical reaction on the fluid dynamics is negligible
4) The effect of buoyancy is negligible
5) The jet is adiabatic
6) The gas and liquid phases travel with the same velocity
7) The flux distributions of the mass $\rho u$, species $\rho u y$, energy $\rho u H$ and momentum $\rho u^2$ are self preserving and Gaussian for all x (9), where :

$\rho$ - mass per unit volumen of the jet at radius r ($kgm^{-3}$)
y - mass fraction of the aerosol at radius r
u - velocity of the jet at radius r ($ms^{-1}$)
H - enthalpy of the jet at radius r ($J\ kg^{-1}$)

The last mentioned assumption merits two remarks : in a recent publication FONDSE et al. (14) suggest that while the jet is self preserving for $x/d_o > 70$, it is only partially so for $x/d_o > 10$. Besides, certain authors like KATAOKA et al. (15) and SPALDING (16) propose other distribution laws which are practically close to Gaussian. Also, the analysis of NEI et al. (17) on the temperature profiles of a reactive jet of steam in liquid sodium is not in contradiction with this hypothesis.

The integral equations of the preceding fundamental variables can be written as follows :

$$2\pi \int_0^{r_\infty} \rho u r dr = ml + mo \quad (3)$$

$$2\pi \int_0^{r_\infty} \rho u y r dr = \frac{(0.5\ MH_2 + MNaOH)}{MH_2O} \quad (4)$$

$$2\pi \int_0^{r_\infty} \rho u H r dr = m_o H_o \quad (5)$$

$$2\pi \int_0^{r_\infty} \rho u^2 r dr = m_o u_o \quad (6)$$

ml : mass flux of the total entrained liquid ($kgs^{-1}$)
$MH_2$, MNaOH, $MH_2O$ : molar masses of hydrogen, sodium hydroxide and water respectively.

The indices c, $\infty$, o and a refer respectively to the center-line, the far-field, the origin and the upstream of the injector.

As MORTON (18) has shown, we can simplify the preceding equations by utilizing a transformed variable :

$$\eta = r/b \qquad (7) \qquad \text{with:}$$

$$b = x\,(\rho_c/\rho_\infty)^{0.5} \qquad (8)$$

$$f_1(\eta) = \rho u/\rho_\infty u_c \qquad (9)$$

$$f_2(\eta) = \rho u y/\rho_\infty u_c Y_c \qquad (10)$$

$$f_3(\eta) = \rho u H/\rho_\infty u_c H_c \qquad (11)$$

$$f_4(\eta) = \rho u^2/\rho_\infty u_c^2 \qquad (12)$$

Substituing the expressions (9), (10), (11) and (12) respectively in (3), (4), (5) and (6), we obtain the following equations :

$$2\pi\, \rho_\infty u_c\, b^2 K_1 = ml + m_0 \qquad (13)$$

$$2\pi\, \rho_\infty u_c\, Y_c\, b^2 K_2 = 2.28\, m_0 \qquad (14)$$

$$2\pi\, \rho_\infty u_c\, H_c\, b^2 K_3 = m_0 H_0 \qquad (15)$$

$$2\pi\, \rho_\infty u_c^2\, b^2 K_4 = m_0 u_0^2 \qquad (16)$$

If the properties are self preserving, $K_1$, $K_2$, $K_3$, $K_4$ are constant coefficients of form :

$$K_i = \int_0^{\eta_\infty} f_i(\eta)\,\eta\, d\eta \qquad i = 1,2,3,4 \qquad (17)$$

For the range of temperature of the jet between 625 K and 1155 K there is no phase change and hence :

$$H_c = DT_c\,(cy + c_2(1-y)) \qquad (18)$$

$$c = (c_1 + 40\, c_3)/41 \qquad (19)$$

$c$, $c_1$, $c_2$, $c_3$ being the specific heats of the aerosol, the hydrogen, the sodium and the sodium hydroxide respectively in J $kg^{-1}K^{-1}$ and $DT_c = T_c - T_\infty$

$c_1$, $c_2$ and $c_3$ are given in Table 1 :

| T | 600 | 900 | 1200 |
|---|---|---|---|
| $c_1$ | 14560 | 14940 | 15445 |
| $c_2$ | 1295 | 1255 | 1293 |
| $c_3$ | 2147 | 2102 | 2057 |

TABLE 1 : specific heats of $H_2$, Na and NaOH (19), (20)

In the domain considered $c/c_2 \approx 1.7$ and if we admit that the constants $K_1$ and $K_3$ are of the same order, we can write, combining (14), (15) and (18), the following equations :

$$\frac{c_2\, DT_c}{H_0} = \text{const}/(1.6 + ml/m_0) \qquad (20)$$

Further, by combining the heat of reaction for the reaction (2) proposed by NEUMANN et al. (21) and the specific heats of steam and liquid sodium between 0 and 700 K (temperature at which the reactants are introduced) we obtain :

$$H_0 = 1.011\;10^7 + 1780\, T_{Na} + 2011\, T_0 \qquad (21)$$

For the entrainment, RICOU and SPALDING (22) propose the following equation for monophase jets, and for $x/d_0 \gg 1$ :

$$\frac{ml}{m_0} = \frac{x}{d_0}\left(\frac{\rho_\infty}{\rho_0}\right)^{0.5} Re_0^{\;-l} \qquad (22)$$

where $l = 0$ for $Re_0 > 30000$ and $l$ varies with $x/d_0$ for $Re_0 < 30000$. $Re_0 = d_0 u_0 \rho_0/\mu_0$ and $\mu_0$ is the viscosity of the fluid at the origin (Paxs).

This equation has been verified by our group (23) to be approximately true for the two-phases situation also, as suggested by SPALDING (16) . But the results obtained by KENNEDY and COLLIER (24) are in partial contradiction with the equation (22) and they propose a zone of zero entrainment.

The chemical reaction possibly plays a role in the entrainment. So it seems logical to describe the entrainment by an expression similar to (22). Hence we will assume that:

$$\frac{ml}{m_0} = \left(\frac{x}{d_0}\right)^{j}\left(\frac{\rho_\infty}{\rho_0}\right)^{k} Re_0^{\;-l} \qquad (23)$$

Further we have also verified (23) that for $x/d_0 > 10$, $ml/m_0 \gg 1.6$; subtituing the expression (23) for $ml/m_0$ in the equation (20), we obtain :

$$\frac{c_2\, DT_c}{H_0} = A\left(\frac{x}{d_0}\right)^{-j}\left(\frac{\rho_\infty}{\rho_0}\right)^{-k} Re_0^{\;l} \qquad (24)$$

## EXPERIMENTAL SET-UP

The experiments were done in the installation JONAS (figure 3) which consists essentially of a cell for the experiments a sodium circuit, a steam circuit, a nitrogen circuit and an evacuation circuit.

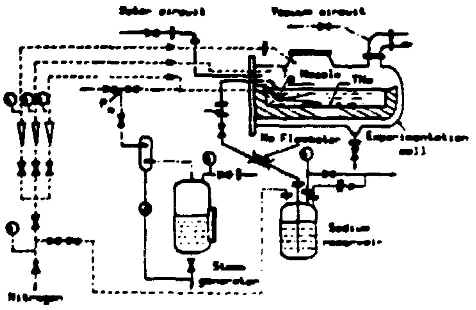
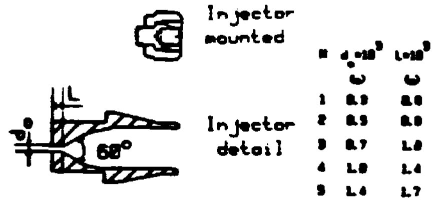


Figure 3 : The schematic of the installation JONAS

The experiments-cell made from 316 TI stainless steel, consists of a well of capacity 3 litres, isolated from the atmosphere by a sliding envelope. The steam is injected through a calibrated injector figure 4, to form a submerged jet in the liquid sodium which fills the well.



| N | $d_o \times 10^3$ (m) | $L \times 10^3$ (m) |
|---|---|---|
| 1 | 0.3 | 0.6 |
| 2 | 0.5 | 0.8 |
| 3 | 0.7 | 1.0 |
| 4 | 1.0 | 1.4 |
| 5 | 1.4 | 1.7 |

Figure 4 : The schematic of the steam injector

The ten thermocouples which measure the temperature profile in the jet (T00 to T09) are fixed on a vertical support facing the injector as shown in figure 5. This support can be displaced along the center line axis by means of a stepper-motor piloted by a TRANSLATEUR IT 60 MICRO CONTROLE. The temperature of sodium is measured by another thermocouple in the well.

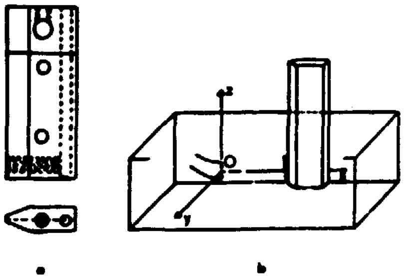


Figure 5 : (a) thermocouple support
(b) positioning of the thermocouple support

The sodium circuit has heating elements to melt the sodium and the well is filled by pressurizing the sodium reservoir with nitrogen.

The steam circuit consists of a steam generator and a super heater. The pressure $P_s$ and the temperature $T_s$ of the steam upstream of the injector are measured by a pressure transducer and a thermocouple. The pressure transducer is connected to a carrier demodulator CD12 VALIDYNE.

The nitrogen circuit permits i) the introduction of nitrogen through the injector to prevent its blockage, ii) the pressurization of the sodium reservoir, iii) the sweeping of the different lines to clean them.

The thermocouples are of the chromel-alumel shielded by inconel and are of 0.5 mm diameter. They are connected to OMNIAMP amplifiers with a gain of 25. The equation connecting the temperature to the output voltage of the amplifiers can be written as :

$$T = 273 + 962.39\,V + 232.49\,V^2 - 783.26\,V^3 + 842.86\,V^4 - 286.93\,V^5 \qquad (25)$$

V : output voltage in V

The output of the pressure transducers and the OMNIAMP amplifiers are connected to an acquisition system consisting of a DATA ACQUISITION CONTROL HP 3497A and a voltmeter HP 3437A.

The acquisition system, as also the TRANSLATEUR IT 60 are connected to a micro-computer HP 9825T through the interface IEEE 488. The system is equipped, besides, with a peripheral memory of 560 kilobytes.

## EXPERIMENTAL PROCEDURE

During the experiment, some or all of the thermocouples are destroyed ; hence their good functioning and their correct positioning are verified before each experiment.

A photograph of the thermocouples fixed to the mobile support permits the measurement of the inter thermocouple distances on the Oz axis. The position in Oy axis is done by the injection of steam in the well filled with water, and the thermocouple support is displaced to align the thermocouples on the axis of the jet. The thermocouples are correctly aligned when the difference in temperature between the steam jet and the ambient water in the well, measured by them, is a maximum. The injection of steam in water permits also a visual verification of the alignment.

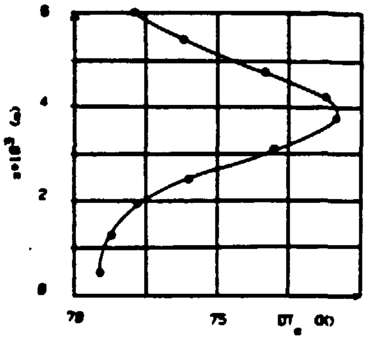


Figure 6 : Injection of steam in water

When these adjustments are over, the experimentation cell is closed and the experiment started. The operations procedure, controlled by the desktop computer, regulates the different phases of the experiment which has six principal stages :

1) Verification of the system (valves, instrumentation)
2) Heating and evacuation of the experimentation cell
3) Filling of the well with liquid sodium
4) Superheated steam generation
5) Injection of dry, superheated steam at regulated pressure $P_s$ as a submerged jet into the liquid sodium in the well and measurement of temperature at different distances in the jet along the injection axis :
   - the acquisition system is verified again

- steam is first let out towards the exterior to eliminate possible condensed water
- then the dry steam is injected into the well and the injection pressure is regulated
- when the pressure of the submerged jet of steam in liquid sodium becomes constant, the micro computer is made to command the displacement of the thermocouple support to a preselected distance z. The pressure transducer and the twelve thermocouple (T00 to T09, Tda and $T_a$) outputs are scanned at a frequency of 20 Hz. After five seconds of measurement, the micro computer commands the displacement of the thermocouple support to a new distance z
- the measurements are made for ten distances along the jet. The results are stored in a floppy disc
- the thermocouple support is displaced sufficiently away from the injector and a new steam injection pressure is selected and the experiment is thus repeated for different steam injection pressures

6) After cooling, the sodium is destroyed and the experiment cell cleaned with water.

## INTERPRETATION OF EXPERIMENTAL RESULTS

The experimental temperature profiles are obtained after smoothening by the method of cubic spline interpolation (25). An example of such a profile is shown in Figure 7.

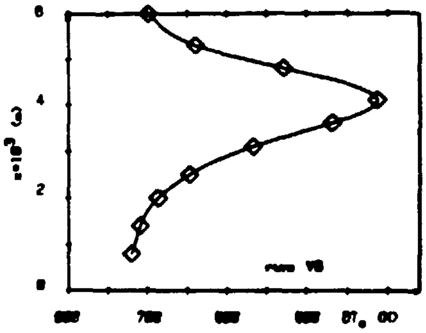


Figure 7 : Experimental temperature profile

About an hundred and fifty profiles corresponding to $T_c$ < 1155 K and $z/d_o$ > 10 have been retained for analysis.

The temperature distribution in a free jet may be represented by an error function (15). The experimental results are fitted to the following curve by the simplex method (26), :

$$T = T_\infty + DT_c \exp\left(-\left(\frac{z - z_c}{r_s}\right)^2 \ln 2\right) \qquad (26)$$

z : ordinate of the jet center line

$z - z_c = r$, the jet radius

b : corresponds to the radial scale characterizing the half property i.e $DT = DT_c/2$ For $r = b$

The mean coefficient of correlation over the profiles retained for the curve so obtained is 0.97, with more than half of them better than 0.99, thus verifying the assumption of an error function distribution for the temperature in the jet. Some such curves are presented in Figure 8.

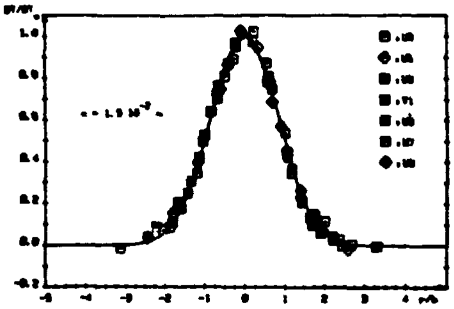


Figure 8 : $DT/DT_c = f(r/b)$

It is now possible to study the parameters of the equation (24). The following expression for $u_o$, $\rho_o$ and $\mu_o$ are obtained as functions of $P_a$ and $T_a$ for sonic conditions :

$$u_o = 22.86\ T_a^{0.5} \qquad (27)$$

$$\rho_o = 1.362\ 10^{-3}\ P_a/T_a \qquad (28)$$

$$\mu_o = 3.36\ 10^{-8}\ T_a - 1.86\ 10^{-6} \qquad (29)$$

j, k, l are obtained by the multiple regression analysis with a coefficient of correlation of 0.76 :

$$\frac{c_1\ DT_c}{H_o} = 3.05\ 10^{-6}\ \left(\frac{z}{d_o}\right)^{-1.1}\ \left(\frac{\rho_\infty}{\rho_o}\right)^{-0.6}\ Re_o^{\ 1.5} \qquad (30)$$

The graph of $c_1 DT_c/H_e$, calculated versus experimentally obtained, are shown on the Figure 9 :

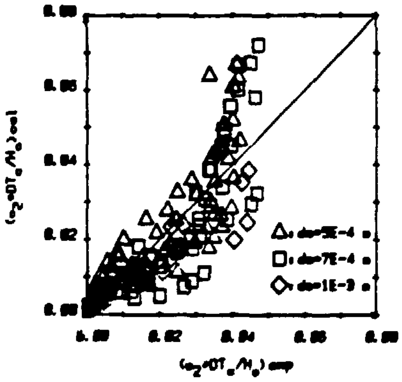


Figure 9 : $(c_1\ DT_c/H_o)cal = f(c_1 DT_c/H_o)exp$

It is found that, at high temperatures and for $x/d_0$ close to 10, the calculated values are higher than the experimental values. The differences observed may be due to various reasons ; we evoke some of them :

- the reaction is unfinished. The equation (21) overestimates then the values of $H_0$.
- the mass flux distribution deviates from the Gaussian when $x/d_0$ is close to 10. CARREAU et al. (23) have noticed such a deviation.
- the entrainment equation does not adequately describe the phenomenon for small $x/d_0$, for the aerosols produced by the reaction at high temperature can alter the Reynolds number. It is interesting to note, in this regard, that the increase in the kinematic viscosity of hydrogen is four-fold in the temperature range of 700-1150 K.

For $x/d_0$ > 20, the differences observed decrease but the number of points experimentally obtained is insufficient to permit any definitive conclusion to the drawn. Besides, if j and k are close to the values obtained from the results of RICOU and SPALDING (22), l is about five times more. This is possibly due to the variation of the Reynolds number in the jet and it is perhaps useful to decide upon a mean Reynolds number for the region 0 to x.

## CONCLUSIONS

In this study of the temperature distribution in a free submerged reactive jet of steam in liquid sodium, we have been able to verify experimentally a few of the simplifying assumptions, for steam flow rates less than 0.5 g/s.

- the temperature profiles can be represented by the error function.
- an approximate equation giving the difference in temperature between the jet axis and the radial far-field has been obtained by an integral method.

The differences observed between the calculated and the experimentally obtained values may be partially attributed to our incomplete knowledge of the entrainement ; this phenomenon is, besides, being studied by our group.

Also, the experiments are continued with higher steam flow rates, to study the temperature profiles for higher $x/d_0$ with a greater accuracy and a well-defined reaction zone.

Further, a study of the coupling of the entrainement with the chemical factors and their influence on wastage is being carried out in our group. The totality of these research efforts, will in all probability, enable us to modelize more completely the phenomenon of wastage.

## ACKNOWLEDGEMENT

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The results contained in this communication are published with their authorization.

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