THE DIVA PROGRAMME: GENERAL PRESENTATION AND FIRST RESULTS

XA0055012

P. DUMAZ
DRN/DER/SIS

B. DUC
DRN/DEC/SECA

CEA-Cadarache,
Saint-Paul-lez-Durance, France

Abstract

The French "Commissariat à l'Energie Atomique" (CEA/DRN, Nuclear Reactor Division) is carrying out a new programme devoted to the thermalhydraulics of steam injectors. This programme was called DIVA. Both experimental and theoretical works are planned. Motivations, objectives, test facility and test section dimensioning of this new programme are presented. A first test series was just performed. The validation of the test section dimensioning and experimental procedures was obtained. These first experimental data are presented and preliminary analyses are given.

1. INTRODUCTION

The use of passive systems to remove decay heat in advanced light water reactor is one way to improve significantly safety. Among those systems, Steam injectors (SI) or condensing ejectors seem to have promising capabilities. The principle of these apparatus is to expand pressurised steam through a converging-diverging nozzle. Steam reaching low pressures, cold water is drawn into the SI, then, steam condenses and transmits momentum to water (part called mixing chamber). In a diffuser, pressurised water is obtained, the pressure being recovered in what looks like a straight shock .

During past 3 years, CEA/DRN studied the potential applications of SI and attempted to develop a SI numerical model using the CATHARE computer code [1] [2].

CATHARE is a two-phase flow code devoted to the thermalhydraulics of LWR accidents [3] [4]. The CATHARE standard module is based on the one-dimensional, two-phase, six-equation thermalhydraulic model. The choice of CATHARE was made because :

- CATHARE is a very general and well validated code;
- with CATHARE, integration within a system model (plant) is very easy (system evaluation);
- It is important to extend the range of CATHARE utilisation.

The development of a CATHARE SI model started within the frame of a CEA/DRN-ENEL (Italian Utility) agreement. ENEL and CISE (an Italian engineering company) designed, built and tested a single stage high pressure SI [5]. This apparatus is able to pump cold low pressure water (less than 0.3 MPa) up to pressures about 10% higher than the steam source pressure (This latter varying from 2 MPa to 9 MPa). The analyses of these results using CATHARE have demonstrated the feasibility of a SI CATHARE model [2] [6].

2. MOTIVATIONS AND OBJECTIVES OF THE DIVA PROGRAMME

One of the initial objectives of the CEA/ENEL agreement was to qualify CATHARE for SI thermalhydraulic conditions. This objective was not reached. Actually, the available experiments were not enough instrumented to achieve this objective. This is the first motivation to undertake a new experimental programme.

On the other hand, other important points have to be mentioned :

- Commercially available SI work below 2 MPa. In a pressurised water reactor, a steam pressure up to 15 MPa (pressuriser) could be used.
- More advanced prototypes (regarding LWR applications) have some important disadvantages: the overflows in the ENEL/CISE apparatus, the heat exchanger in the PAHRSEC system [7] (schematised on Figure 1).
- Some basic phenomena controlling the SI behaviour are not actually well understood (liquid film atomisation, abrupt pressure recovery). .

From those considerations, CEA/DRN made the decision to undertake new experiments in the frame of its innovative activities. A CEA working group, involving several laboratories, is in charge to define and to manage the programme since the beginning of 1996.

Three main objectives were identified :

- To study thermalhydraulic basic phenomena : shock waves and supersonic flows in two-phase flow, liquid film atomisation, dissipation processes.
- To develop and to qualify a CATHARE SI model.
- To develop a data base and an expertise required to design and to evaluate innovative configurations using SI.

3. THE TEST FACILITY

To perform these experiments, it is necessary to supply several kilograms per second of steam. One looked for available boilers in CEA laboratories and one chose the CLAUDIA facility located on the Cadarache research centre. This facility includes a 30 MW fuel-oil boiler which can supply 11 kg/s of steam up to 3 MPa. This steam pressure is the main disadvantage of CLAUDIA facility but it was thought to be sufficient in the first part of the programme regarding investments required by other facilities.

The steam line coming from the boiler is equipped with an isolating valve and a control valve. The demineralized water supply is made by a 10 m^3 tank and a 0.033 m^3/s pump. This water can be pressurised up to 3 MPa and heated up to 200°C. A valve controls the water flowrate. Downstream the test section, a control valve regulates the back pressure.

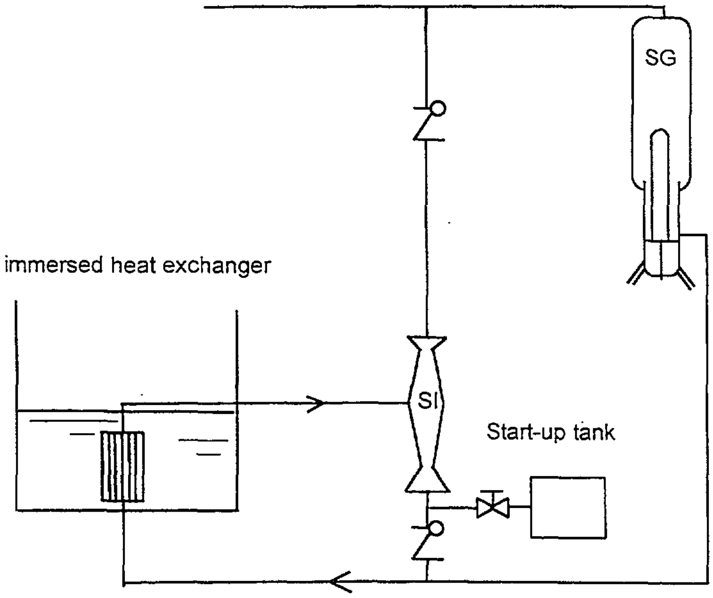

FIG. 1. Recirculation configuration [7].

4. REFERENCE EXPERIMENTAL CONDITIONS

In order to choose, as far as possible, representative experimental conditions, it was decided to choose a reference application, the steam generator auxiliary feedwater system (AFW), and to seek a scaling factor of one (in order to avoid, as far as possible, a scaling analysis). In a 1300 MWe French nuclear reactor, the required flowrate per steam generator is 12.5 kg/s which means a power of 33 MW at 8 MPa. The CLAUDIA facility limitations dictate the choice of the reference steam pressure: 3 MPa.

At least two SI system configurations could carry out the steam generator AFW function :

- the injection configuration (Figure 2).
- the recirculation configuration (Figure 1), mainly developed in Russia [7].

It is intended to study both configurations which will necessitate two different test sections.

For the injection configuration, a reference water flowrate of 12.5 kg/s is chosen, the corresponding steam flowrate being estimated to be about 2 kg/s. In recirculation configuration, 33 MW at 8 MPa means a steam flowrate of 14 kg/s (all the steam produced flows through the SI). At 3 MPa, this gives 5.3 kg/s, the steam flowrate being almost proportional to the pressure. From published data, the water flowrate was estimated to be 70 kg/s. This latter value exceeding the facility capability (see paragraph above), water and steam flowrates had to be reduced. In order to limit the number of parameters, the previous steam flowrate of 2 kg/s was chosen.

Our experimental programme started with a test section devoted to injection configurations. In the following sections, this configuration only will be discussed.

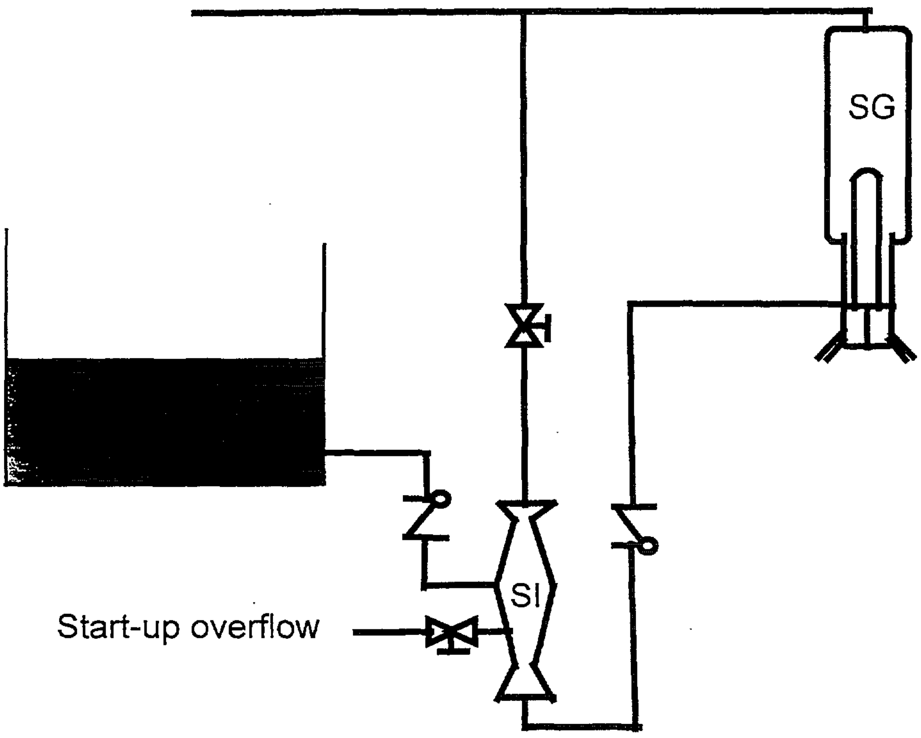

FIG. 2. Injection configuration.

5. TEST SECTION DIMENSIONING

The first choice made was to use a central steam injection with an annular water injection. This was because the high pressure prototypes known [5] [7] use this option.

To have useful data to develop and qualify new models, a regular test section is highly desirable. It was decided to do not use overflow lines (Figure 3). This requires adequate choices of the experimental procedures and the test section dimensions. This means one tolerates a reduction of the test section performance (pressure recovery) which does not matter for basic studies.

For the steam nozzle, the two important dimensions are the throat diameter: Dc and the nozzle outlet diameter: Ds. The former gives the steam flowrate (choked flow) and the latter the nozzle expansion ratio, Pvo/Ps (Pvo the inlet steam pressure, Ps the steam nozzle outlet pressure). for injection configuration, a ratio of 100 was chosen. Both dimensions were calculated using standard equations of converging-diverging nozzles with an isentropic exponent of 1.2. These gave a throat diameter of 25 mm and an outlet diameter of 90 mm.

For the mixing chamber, the most important parameter is the throat diameter, D_m, A design criterion is derived using the momentum balance.

Upstream the pressure recovery location (called the shock), assuming a constant pressure and neglecting all momentum losses, one has:

$$Q_{vo}.V_s + Q_{lo}.V_{lo} = (Q_{lo} + Q_{vo})V_l^-$$

and through the shock :

$$(Q_{lo} + Q_{vo})V_l^- + P^+.S = (Q_{lo} + Q_{vo})V_l^+ + P^+.S$$

where :

Q_{vo} , the inlet steam mass flowrate
Q_{lo} , the inlet water mass flowrate
V_s , the exit velocity of the steam nozzle
V_{lo} , the inlet liquid velocity

V_l^- , P^- are the liquid velocity and the pressure just upstream the shock and

V_l^+ , P^+ just downstream.
S is the "shock" flow area.

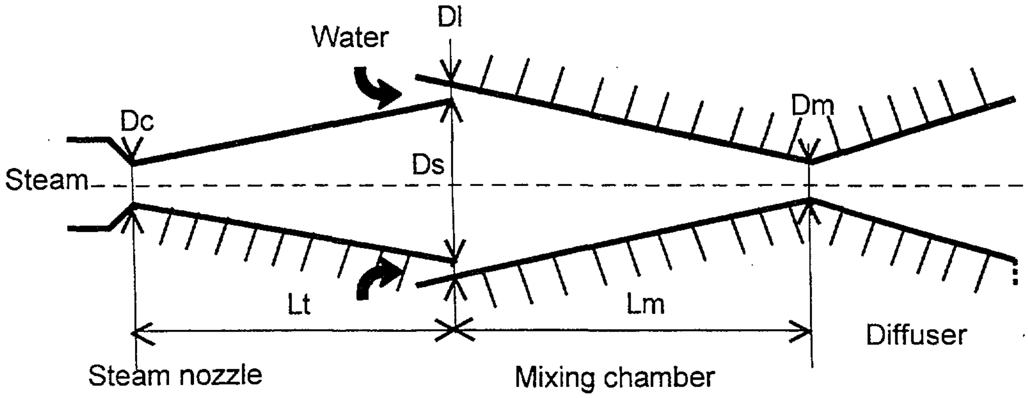

FIG. 3. Schematic of the test section.

Combining these two equations, one finds:

$$P^+ - P^- = \frac{Q_{vo}V_s + Q_{lo}V_{lo}}{S} - \frac{(Q_{vo} + Q_{lo})^2}{\rho_l . S^2}$$

$P^+ - P^-$ has a maximum value (Figure 4) for $S = S_0 = \frac{2.(Q_{vo} + Q_{lo})^2}{\rho_l(Q_{vo}.V_s + Q_{lo}.V_{lo})}$, from stability considerations [8], one must have : $S \geq S_o$., This means $D_m \geq 15\,mm$ for the injection configuration. To avoid the use of overflow ports and to reduce the stalling risks, it is desirable to have a high value of S (which means a reduction of the apparatus performances). After all, the choice $D_m = 30\,mm$ was made. Given the significance of this parameter, a second diameter, 20 mm, will be tested.

The length of the apparatus was determined assuming half angles of 3°.

6. INSTRUMENTATION

In these SI experiments, measurements have to be made in difficult conditions : high pressures, temperatures and velocities, vibrations.

In the first test series, the test section dimensioning and the experimental procedure have to be validated. Therefore, conventional measurements are used mainly. These consist in the profiles of pressure and internal wall temperature (steam nozzle, mixing chamber, diffuser, see Figure 5). Of course, standard boundary conditions are also measured. One also used an optical fibre mounted on an axial probe which moves along the diffuser. This fibre should measure the centreline local void fraction

To measure the two-phase flow structure inside the mixing chamber, a multibeam X-ray densitometer is developed [9]. On each axial position, 31 beams will give an accurate determination of the local void fraction. The main drawback of this technique is to require a specific test section (to minimise the wall thickness) which explains that, in first tests, test section dimensioning must be validated.

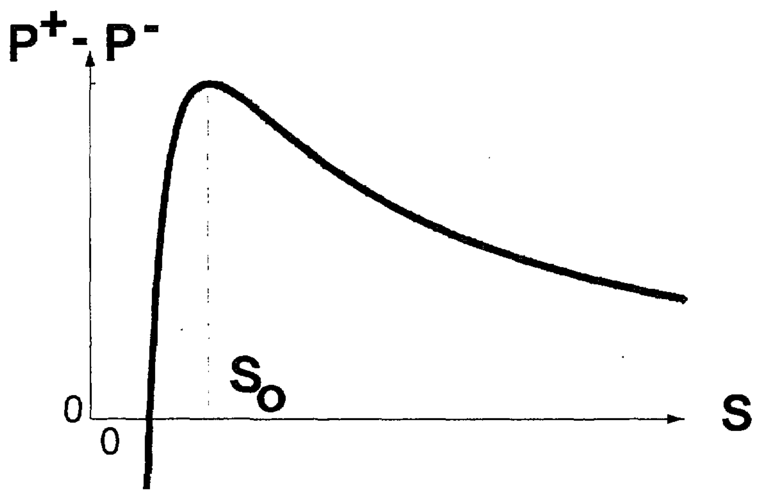

FIG. 4. $P^+ - P^-$ *in function of the shock area.*

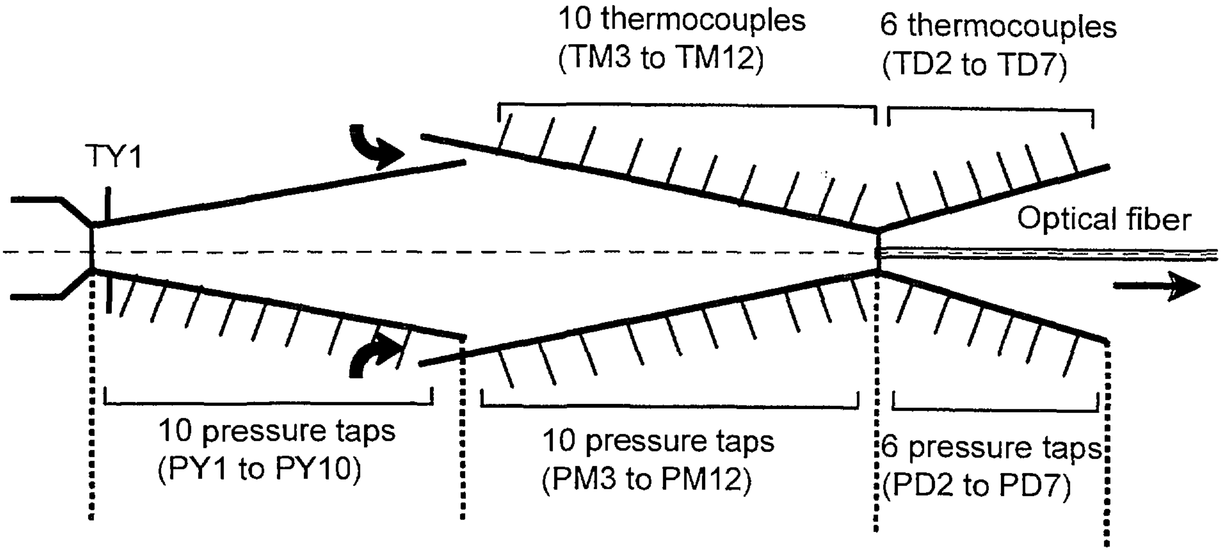

FIG. 5. Instrumentation.

7. TESTS DESCRIPTION AND RESULTS

The boundary conditions which are controlled and which determine the apparatus behaviour are : the steam pressure Pvo, the water flowrate Qlo and the back pressure BP. It should be mentioned that in this first test series the steam is saturated and the injected water is at room temperature. At the beginning of the test, the back pressure is always close to the atmospheric pressure and can be increased by a control valve.

Two procedures were tested to start-up the apparatus. The former procedure consists in opening the steam flow first, then to increase the water flowrate and finally the back pressure (see Figure 6, the pressure profiles at different times). By this way, a minimum water flowrate is necessary to obtain a stable behaviour. This stable behaviour appears to be also the limit to have a started SI (with low mixing chamber pressure). The latter procedure consists in opening first the water flow at a value higher that the previous limit and then to open the steam valve. This procedure gives a smooth start-up of the apparatus.

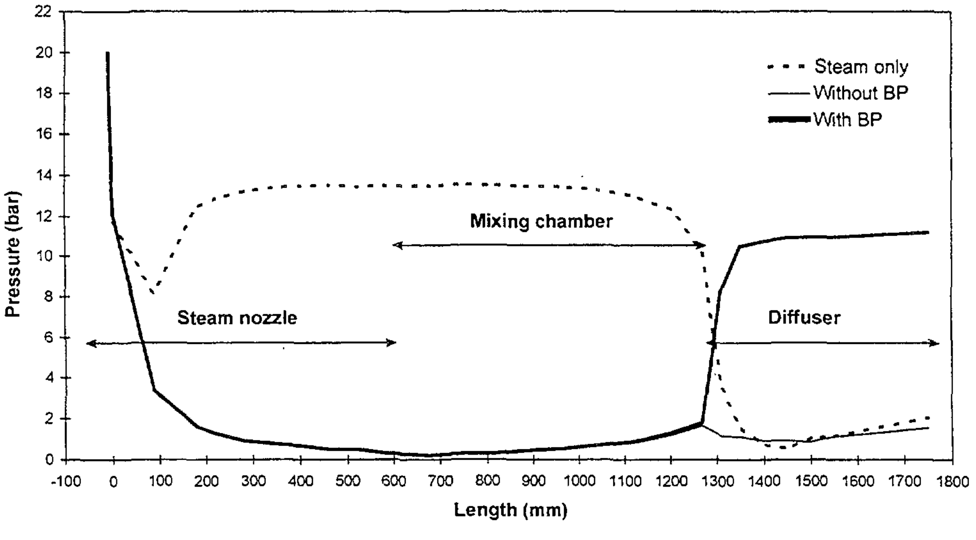

FIG. 6. Pressure profiles for a 2 MPa test.

The test already performed are summarised in the Table I. The start-up procedure is indicated (steam or liquid) as well as the shutdown procedure.

To have a smooth test shutdown, the steam valve is closed first. The other possibilities explored are the back pressure increase and the water flowrate reduction. This leads to a less smooth shutdown (noise and vibrations). Due to an unexpected water flowrate limitation (ongoing analyses), one does not obtain the apparatus shutdown by an increase of the water flow.

The pressure profiles (Figure 6) well illustrate the different test phases. In pure steam flow, one has critical flows at the two throats locations (steam nozzle and mixing chamber). Then, the mixing chamber pressure is high. With a high enough water flowrate, a low mixing chamber pressure is obtained. During this phase, from fluctuating, the pressure measurements become stable (Figure 7). The closure of the back pressure valve causes a pressure increase in the diffuser and the shock appearance. This operation does not modify the mixing chamber pressure. This is an indication of the supersonic nature of the mixing chamber two-phase flow.

We had some problems with the optical fibre (vibration of the mechanical support, leak). Finally, the fibre was broken during the 2 MPa test (back pressure of 0.47 MPa). However, interesting signals were recorded demonstrating the usefulness of this measurement.

8. PRELIMINARY ANALYSES

These analyses are based on energy and momentum balances. Their results are summarised in Table II. Some CATHARE calculations were already run, they require further analyses.

Using the global energy balance, one can calculate the outlet temperature (Tout cal) whether the exit flow is a one-phase flow. This is the case when the back pressure is enough high. For the 2 MPa tests, the agreement with the experimental data (Tout data) is very good. For the 1 MPa tests, the energy balance gives a slight overestimation of the exit temperature.

TABLE I. MAIN PARAMETERS OF THE PERFORMED TESTS

Pvo (MPa)	Qvo (kg/s)	start-up, Qlo (kg/s)	Qlo (kg/s) nom / max	Shutdown	Back Pressure (MPa)	Optical fibre
1	0.75	Steam, 5.2	6.6	BP	0.1 to 0.59	no
1	0.76	Steam, 6	7	Steam	0.1 to 0.2	yes
1	0.77	Liquid, 7	7	min Qlo, 4.4	0.1 to 0.4	yes
1	0.75	Liquid, 5.6	5 / 12.5	Steam	0.1	no
2	1.38	Steam, 7	10 / 18.4	Steam	0.1	no
2	1.41	Steam, 7.5	8.33	BP	0.1 to 1.14	no
2	1.37	Liquid, 8.5	8.5	Steam	0.1 to 0.47	yes
2.8	2	Liquid, 8.9	8.9	Steam	0.1	no

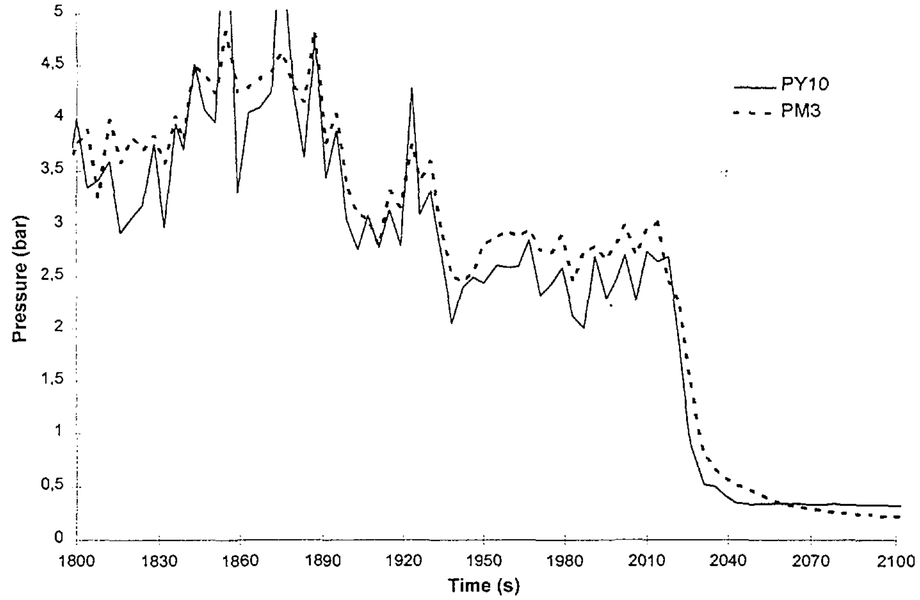

FIG. 7. Pressure variations during SI start-up.

Using a partial energy balance (up to the end of the mixing chamber), one can calculate the mixing chamber condensation rate (Qc). One has:

$$Q_{vo}\cdot h_{vo} + Q_{lo}\cdot h_{lo} = (Q_{lo} + Q_c)h_{l(TM12)} + (Q_{vo} - Q_c)h_{vsatl(PM12)}$$

where h is the specific enthalpy of steam, subscript v, of liquid, subscript l.

TABLE II. PRELIMINARY ANALYSES

Pvo (MPa)	Qvo (kg/s)	Qlo (kg/s)	Qc cal (kg/s)	ΔTsat-12 (°C)	Tout data (°C)	Tout cal (°C)	Pout data (MPa)	Pout cal (MPa)
1	0.75	6.74	0.61	22	89	91	0.59	0.88
1	0.78	6.9	0.64	20	87.5	92		
	0.75	4.7	0.56	17				
1	0.76	9.35	0.65	25.3				
	0.76	12.3	0.67	30.5				
2	1.38	10.3	1.16	22				
	1.39	18.3	1.22	35.5				
2	1.41	8.3	1.1	19	117	117	1.14	1.6
2	1.38	8.45	1.1	18	117	117		
2.8	2	8.9	1.41	19				

PM12 and TM12 are the pressure and temperature measurements at the end of the mixing chamber. This equation means that at the end of the mixing chamber the steam is assumed to be saturated and the water subcooled at the temperature TM12 (this being a questionable assumption). Furthermore, the kinetic energy is assumed to be negligible. The condensation rates obtained appear to be not much dependant of the water flowrate. It seems also that a significant part of steam is not condensed at the end of the mixing chamber (about 20 %). Another interesting result is the increase of the water subcooling (ΔTsat at the location of TM12 and PM12) with the water flowrate. A preliminary conclusion could be that the condensation phenomenon in the mixing chamber is not limited by the liquid side but rather by the vapour side.

Using the momentum balance of the Section 5, the exit theoretical maximum pressure is calculated (Pout cal). It can be noticed that the maximum back pressure obtained is about 70% of this theoretical pressure. This looks quite good since the theoretical calculation assumes no losses at all.

9. CONCLUSIONS

The first tests of the DIVA programme have fulfilled the objectives of dimensioning and test procedures validations. In particular, the choice made to avoid the use of overflows was confirmed. Some interesting features of our apparatus were found out : unstable regime, low momentum losses.

The experimental programme will continue the next two years with the test section devoted to recirculation configuration and with the use of the X ray densitometer. From the modelling point of view, one will have to confirm the CATHARE capabilities regarding the thermalhydraulics of steam injectors.

REFERENCES

[1] AUJOLLET, P. *et al,* "CATHARE detailed modelling of a steam injector and comparison with experimental data"; European two-phase flow group meeting, Piacenza, June, 1994

[2] DUMAZ, P.; MAZZOCCHI, L.; VANINI, L.; "Analyses of steam injector experiments" ARS 97 conference, Orlando, 1997

[3] BARRE, F., *et al,* "New developments in CATHARE2", Nureth 6, Grenoble, Oct 1993

[4] MICHAELLI, J. C. et al, "CATHARE code development and assessment methodologies" ANS Winter Annual meeting, San Fransisco, Oct/Nov, 1995

[5] CATTADORI, G. *et al,* "A single stage high pressure steam injector for next generation reactors : test results and analysis" Int J Multiphase Flow, vol 21, p591-300, 1993

[6] DUMAZ, P.;DUC, B.,"Status of steam injector studies at CEA" ICONE5 conference, Nice, 1997

[7] SOPLENKOV, K. I., *et al,* "Design and testing of passive heat removal system with ejector-condensor" IAEA Tech Meeting, Piacenza, May 1995

[8] IRODOV, V. F.; and ALAD'YEV, T.; "Calculation of the flow in a condensing ejector" Fluid mech, Soviet Res, vol 4, p99, 1975

[9] JEANDEY, C.;"Multibeam X-ray densitometer for flow pattern and void fraction determination in steam water mixtures" mes in polyphase flow, Edited by TR Heidrick and BR Patel, ASME book nr 100209