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Calorimetry measurements during high energy discharges at Tore Supra

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Abstract: One particularity of Tore Supra is that the Plasma Facing Components (PFCs) are actively cooled, allowing research on long duration and high energy discharges.

During a discharge, a large part of the energy is dissipated in the heating generators (ICRH, ECRH and LHH) and auxiliaries. It is transferred to the primary cooling loops (B50 and B60). The energy which is injected in the plasma is totally recovered by the PFCs primary cooling loop B30. The primary loops are cooled via heat exchangers by a secondary loop. The previously existing limitations of the complete Tore Supra cooling system were due to the heat exchange performance to the secondary loop.

From 2001 to 2003, the various primary loops have been upgraded and during the 2003 experimental campaign, significant results were obtained, particularly during non inductive discharges with an injected energy by the Lower Hybrid Current Drive (LHCD) system of up to 1.1 GJ.

For the long and high energy discharges, the agreement between the energy measured by the calorimetry on the PFCs cooling loop and the HF energy is very good (90 to 95%). Furthermore, calorimetry measurements on the various cooling loop allow to assess the global operation of the cooling system.

1. Introduction

Tore Supra is the only tokamak to be equipped with a pressurized water loop which cools all the Plasma Facing Components (PFCs), allowing the achievement of long duration and high injected energy discharges. A new set of PFCs were implemented in the framework of the CIEL project [1]. The objectives concerning the heat removal characteristics were then significantly increased : 25 MW during several hundreds of seconds requiring an upgrade of the dedicated primary cooling loop. The CIMES project [2], launched in 2001, aims to increase the power and the energy injected in the plasma with the RF heating systems, firstly with the Lower Hybrid system. Operations of up to 1000s were considered, requiring the upgrade of the generators primary cooling loops.

The paper presents the main characteristics and operation modes of the Tore Supra cooling system. It will also give the description of the calorimetry diagnostic and a detailed analysis of the PFCs calorimetry measurements for discharges with injected energies in the range 400 MJ to 1.1GJ.

2. Description and characteristics of the Tore Supra Cooling loops

The cooling system of Tore Supra consists in three primary loops. One (B30) is used to cool the Plasma Facing Components (PFCs) and the two others (B50 and B60) cool the auxiliary heating generators and their auxiliaries. These loops transfer the thermal power removed from the components to a secondary loop via heat exchangers.

The B30 (Figure 1) is a pressurized water loop which operates at 150°C or 120°C during the experiments or up to 200°C for the baking of the PFCs. The pressure level is adapted to the operation temperature between 8 bar to 30 bar. The flow in the heat exchanger E30 is monitored to maintain a constant temperature at the outlet of the mixer M30. The E30 heat exchanger has presently a maximum capacity of 9 MW.

The B50 and B60 principle schemes are similar (Figure 2). The Lower Hybrid generators are cooled by loop B60 and those of the Ion Cyclotron, Electron Cyclotron and Diagnostic Neutral Beam by loop B50. They operate at relatively low temperature (<90°C) and are not pressurized (P = 0.7 bar). The maximum temperature at the outlet of the generators must be kept below 90°C which requires that the temperature at the inlet of the pump is < 31°C. If this threshold is reached the generators are switched off.

The maximum capacity of the heat exchanger E50 or E60 is presently 3 MW, while the power to be removed from the generators and auxiliaries can reach 20 MW. To increase the discharge duration to several hundreds of seconds (CIMES project) an upgrade of the B50 and B60 loops was required. A first part was achieved in 2002. To reduce the power transferred to the secondary loop during a discharge, a tank of 75 m^3 was added on the return line. One part (25%) of the flow is derived in the heat exchanger thus limiting the heat transfer and the remaining part of the water circulates through the tank. The two flows are mixed at the inlet of the pump so that the temperature remains below 31°C. At the end of the discharge, the flowrate in the loop is reduced. All the flow circulates in the tank which is then cooled down to 25-27°C. In 2004 the two heat exchangers have been upgraded to 5.8 MW.

The secondary loop is cooled by 2 forced draft cooling towers corresponding to a maximum thermal exchange capacity of 11 MW. The temperature of the water of the loop at the outlet of the cooling towers is in the range 18°C and 27 °C depending on the humid bulb outdoor temperature. This low temperature level is required for the B50 and B60 loops but also by continuous systems such as cryoplant and HVAC compressors with require temperature between 20 to 27°C.

3. Thermo-hydraulic analysis of the loops during high energy discharges

One of the objectives of the Tore Supra experimental program is the achievement of long duration non inductive discharges with high energy injected in the plasma. Since 2002 several attempts to reach 1 GJ injected in the plasma occurred with increasing injected energies. During the 2003 experimental campaign, significant results were obtained, particularly during non inductive discharges with an injected energy by the Lower Hybrid Current Drive (LHCD) system of 1.1 GJ. This value was obtained during the 32299 discharge which lasted 378 sec.

The thermo-hydraulic behaviour of the cooling system have been analysed during these discharges to check its operation. The profiles of the thermal power injected in the B60 loop and of that transferred to the secondary loop is presented in figure 3 (Figure 3) showing the important reduction of this last parameter and the effect of the storage. Figure 4 (Figure 4) gives the corresponding temperature profiles. It shows that the B60 didn't reach its operational limits during this discharge. TT64 remained below 31°C and the maximum water temperature at the upper part of the tank (TT604) was below 44°C. A recovery time of 3800 sec was required to cool down the storage tank for the following discharge in which 1 GJ was injected in the plasma.

The thermal powers in the secondary loop (Figure 5) reached 7 MW well below the exchange capacity of the towers (11 MW). The maximum contribution from the B30 was 2.5 MW while a maximum value of 3.2 MW was injected in the plasma.

4. Calorimetric analysis of high energy discharges

The PFCs are cooled by the B30 by five sub-circuits. The upper one feeds in parallel the 6 modules of Internal First Walls (IFW), bumpers and electrons ripple loss collectors. Each module has a toroïdal extension of 60°. The distribution lines for each component are individualized at the outer of the machine and are individually equipped with a temperature sensor. A flowmeter was set-up on each module.

Three sub-circuits are used for the components connected to the medium ports : 3 ICRH antennas, 2 LHH launchers, 1 ECRH antenna and the Antenna Gard Limiter (AGL). Each sub-circuit feeds in parallel two 60° toroïdal extension modules. Each circuit is equipped with the calorimetric instrumentation allowing the measurement of the thermal power exhausted from the component (Outlet temperature measurement, flowmeter).

The lower part circuit feeds the 6 modules of the Toroidal Pumped Limiter (TPL), a high flux component designed to extract power up to 15 MW. The TPL is a flat limiter made of 12 sectors of 30° toroïdal extension each, a module corresponding to two 30° sectors. A temperature sensor is available at the outlet of each sector, while a flowmeter only exists for a 60° module.

During the discharges, the pumps are monitored by differential pressure transmitters leading to constant flow conditions in the loop. As all the lines connected to the components are not equipped with a flowmeter, a calibration is required at the beginning of each experimental campaign. A portable ultra-sonic flowmeter based on the transit time principle is used. The sensor is put at the outer part of the pipe after the thermal insulation material has been removed. A complete calibration has to be repeated if a component is removed.

Calorimetry results were used previously for TPL trimming experiments and the accuracy of the diagnostic was established for low energy ohmic discharges [3]. But the high energy long duration discharges achieved in 2002-2003 give the opportunity to assess the calorimetry measurements. For these discharges a good agreement concerning the energy balances between the injected energy in the plasma and the thermal energy exhausted from the PFCs can be noted (Figure 5). The deviation is less than 10% except for the 30414 discharge (20%). This can be explained by the fact that the temperature at the inlet of the tokamak increased during the discharge and one part of the energy stored in the components could not be measured accurately. This condition is essential to obtain accurate measurements with the calorimetry. The exhausted thermal powers are measured with a redundancy. One measurement is made at the global machine level and an other one is the sum of measurements on each B30 sub-circuit. Figure 6 presents the comparison of the two cumulated thermal energy profiles for the 32299 discharge. It can be noted that a better stability is obtained if the sum of the various sub-circuits is considered.

5. Conclusion

The cooling system of Tore Supra has been modified and upgraded in the last years allowing to exhaust the thermal power from the PFCs and heating generators for high energy and long duration discharges. Calorimetric instrumentation is available on the PFCs cooling loop and thermal energy balances can be produced. The power on the various PFCs can be measured depending on the time response of each component . For the high energy discharges achieved in 2002-2003 the agreement is quite satisfactory, showing the interest of such a diagnostic. The calorimetric measurements on the other loops are also used to check the proper operation of the cooling system. Calorimetry is a reliable diagnostic. It is particularly powerful for the assessment of the powers on the various PFCs.

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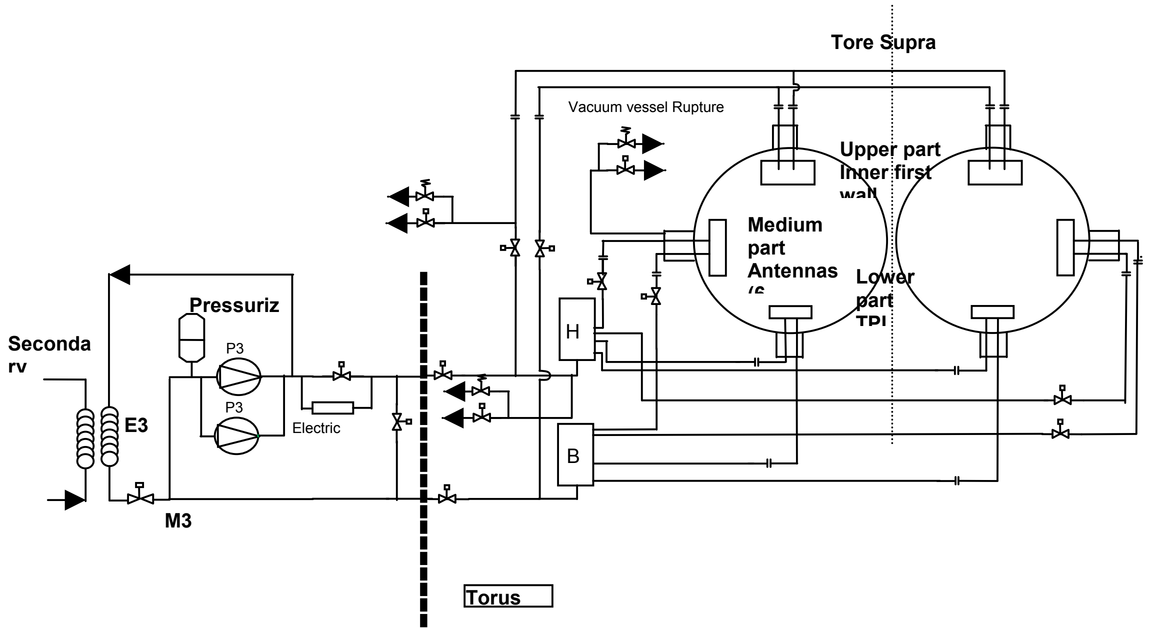
[3] JC.Vallet et al, Calorimetry in Tore Supra. An accurate tool and a benchmark for ITER , Journal of nuclear materials 313-316 (2003) pp 706-710

Figure Caption

Figure 1 : PFCs water cooling loop B30 diagram
Figure 2 : Generators and auxiliaries water cooling loop B60 diagram
Figure 3 : Power profiles in the B60 primary loop during discharge 32299
Figure 4 : Temperature profiles in the B60 during discharge 32299
Figure 5 : Power balances for high energy discharges
Figure 6 Cumulated Thermal Energy exhausted from the PFCs (discharge 32299)



PFCs primary cooling loop B30

figure 1 (1/2 pp)

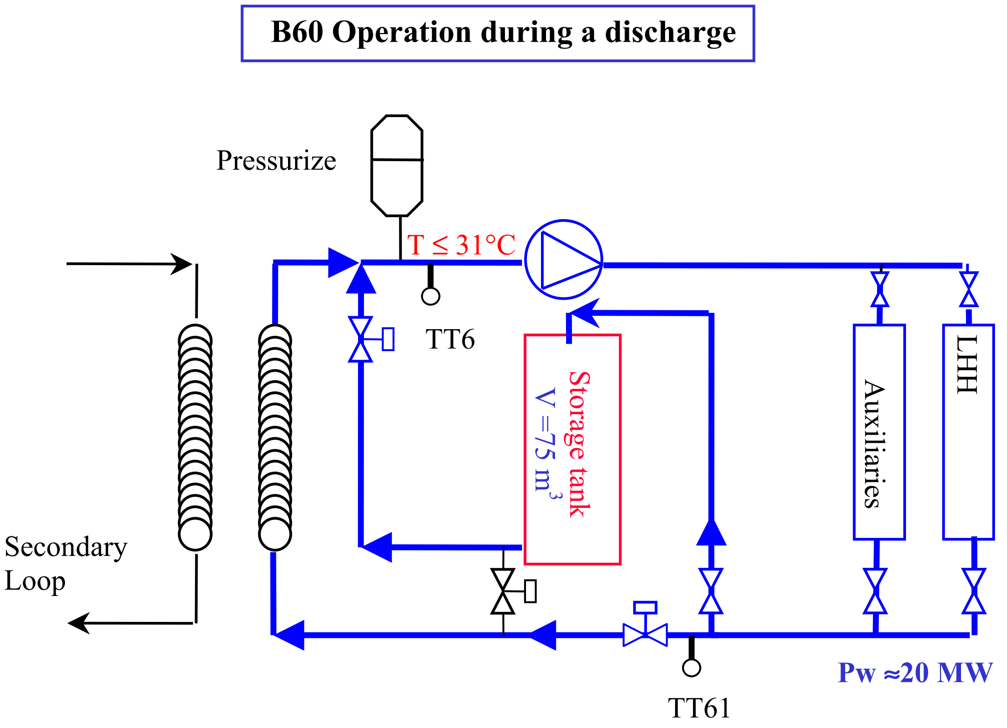


figure 2 Generators and auxiliaries water cooling loop B60 diagram (1/6 pp)

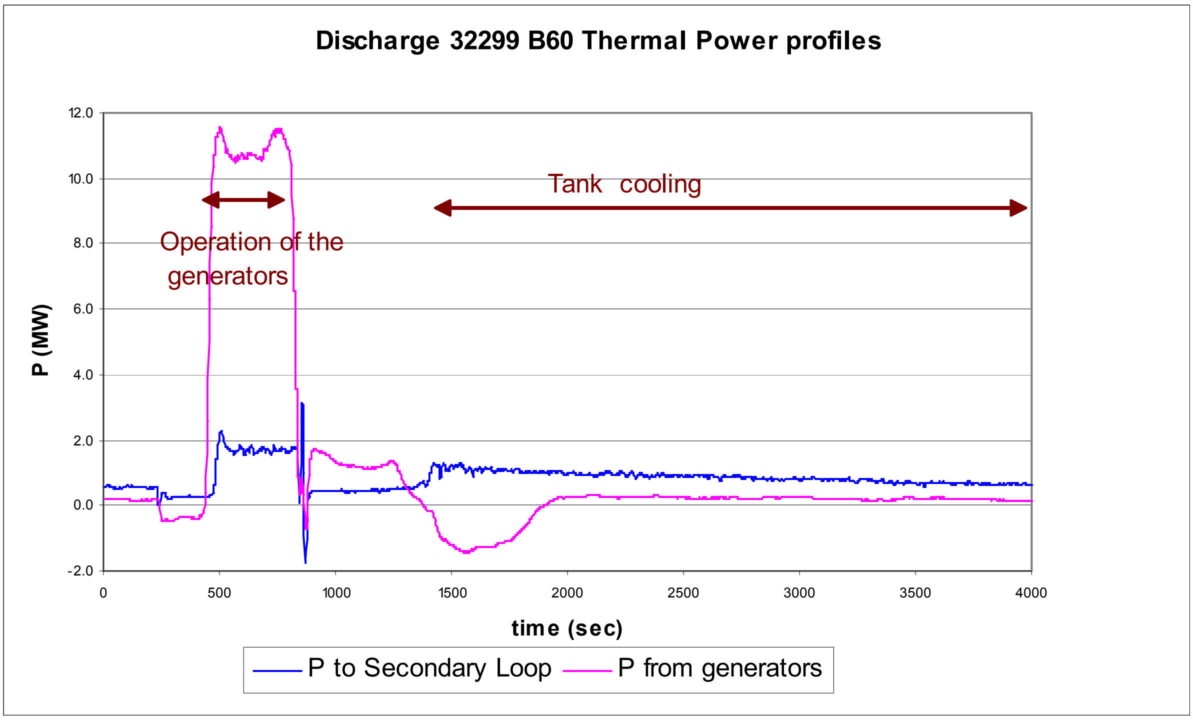


Figure 3 Power profiles in the B60 primary loop during discharge 32299 (1/6 pp)

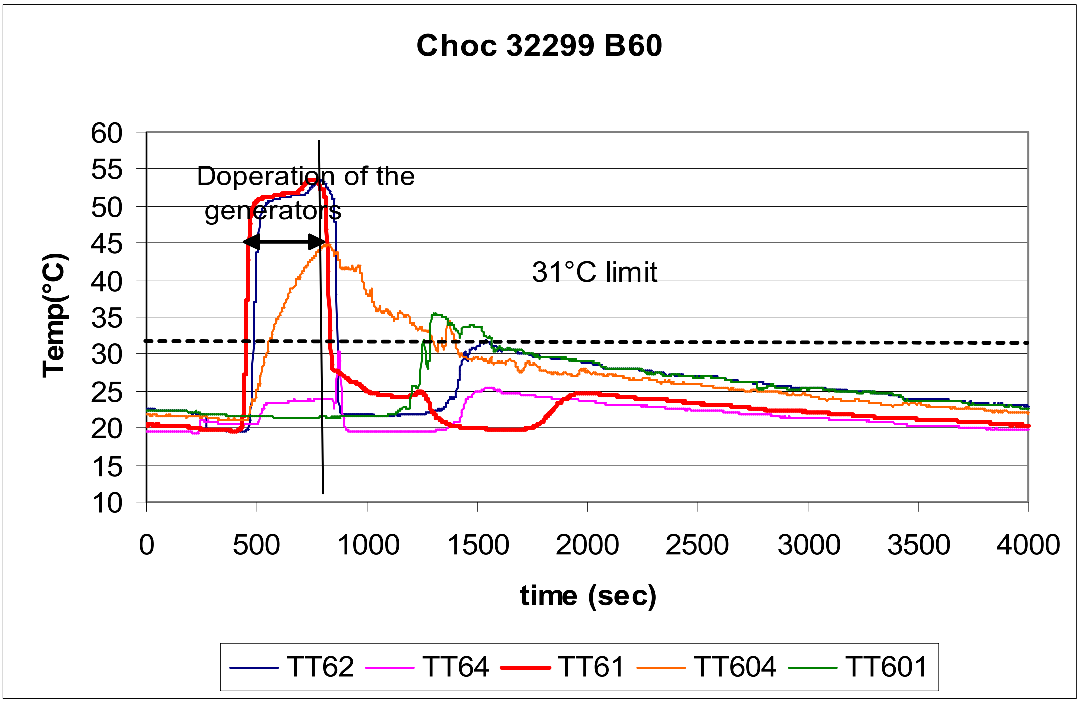


Figure 4 Temperature profiles in the B60 during discharge 32299 (1/6pp)

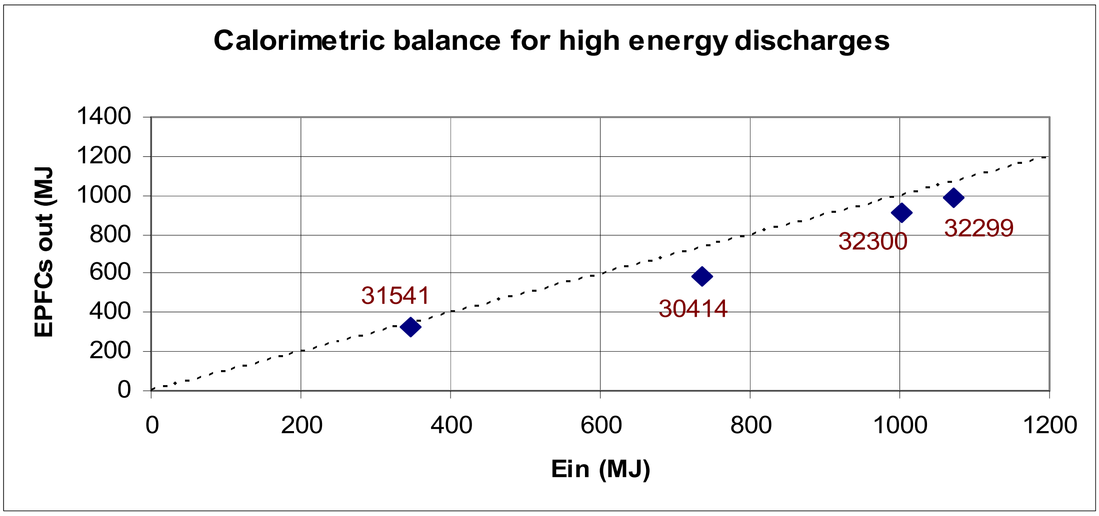


Figure 5 Power balances for high energy discharges (1/6 pp)

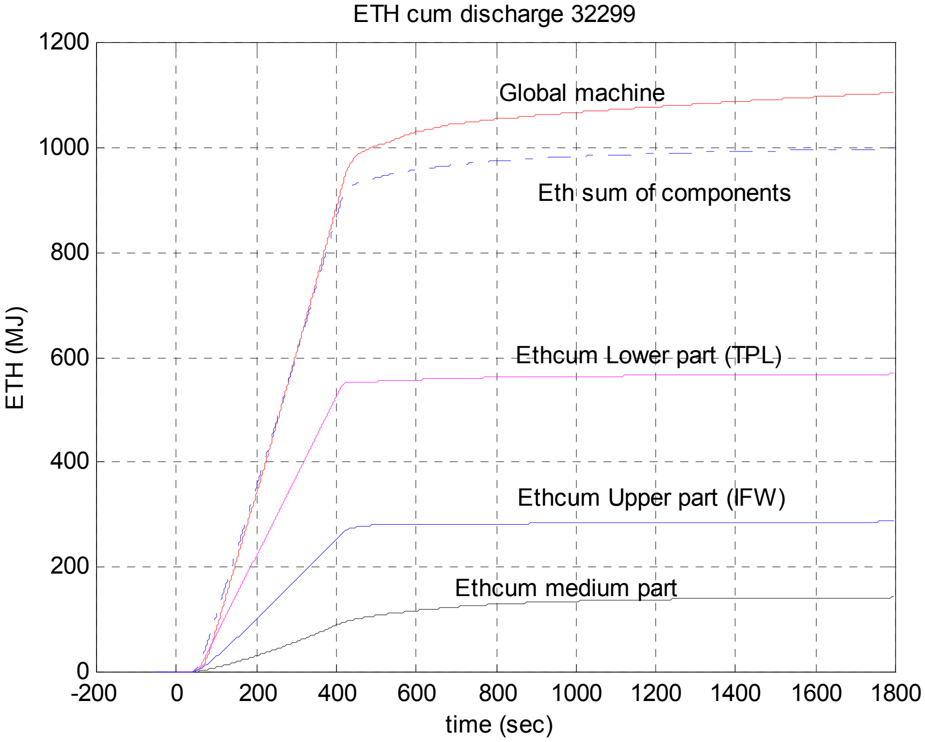


Figure 6 Cumulated Thermal Energy exhausted from the PFCs (discharge 32299) (1/6 pp)