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Short description*

1. Helical Coil Steam Generator facility
2. Passive Emergency Heat Removal System

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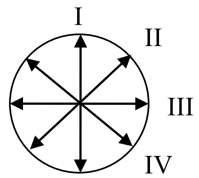
1. HELICAL COIL STEAM GENERATOR FACILITY

The test section, an helically coiled AISI316 SS steam generator (SG) tube, is framed into an open loop facility built inside the boiler building of the "Emilia" power station in Piacenza where SIET labs are located.

The tube has an inner nominal diameter of 12.53 mm, an outer nominal one of 17.15 mm and a length of 32 meters. Test section tube is composed by 5 verges of 6 meters and 1 tube of 2 meters preventively coiled and welded together. Measures made with digital calibre with an accuracy of 1/100 mm on tube inner and outer diameters on a sample straight tube of the same verges used for the test section, showed a maximum difference between measured values and nominal one of 0.44% (table 1), underlining the validity of nominal values.

Table 1. Sample straight tube inner and outer diameters measured with 1/100 mm accuracy digital calibre

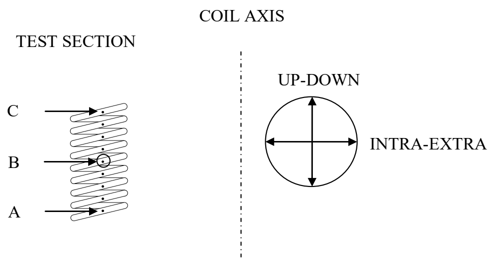
Measure number	I	II	III	IV	mean	nominal	Relative difference [%]
Inner diameter [mm]	12.50	12.43	12.53	12.50	12.49	12.53	-0.32
Outer diameter [mm]	17.23	17.24	17.22	17.22	17.23	17.15	0.44



Further measures taken along the coiled test section, namely at the beginning, in the middle and at the end, on tube outer diameters showed an ovalization (here defined as the ratio between the difference of two orthogonal diameters and tube outer diameter nominal value) of tube outer diameter that never exceed 1.22% (table 2).

Table 2. Test section tube outlet diameters and relative ovalization measured with 1/100 mm accuracy digital calibre

Measure location	A	B	C
D_UP-DOWN [mm]	17.17	17.09	17.08
D_INTRA-EXTRA [mm]	16.96	16.91	16.92
Ovalization [%]	1.22	1.05	0.93



This ovalization was considered negligible in hydraulic and electric calculations, i.e. the nominal straight values of tube inner and outer diameters were considered valid for all the calculations regarding the test section.

Tube inner surface roughness have been measured on the same straight sample used for inner and outer diameters measures. A total of six measures, three on one side and three on the other of the sample, gave a mean roughness of 3.08 μm (maximum value 3.5 μm, minimum value 2.5 μm). Tube roughness plays a minor role on frictional pressure drops in the two phase pre-dryout region, being tube wall eclipsed to vapour core flow by the liquid film in the annular regime and being dominating the interaction between vapour core with liquid film in the dissipative phenomenon.

Nevertheless in the single phase regions, especially for the superheated vapour where Reynolds numbers exceed 600000, tube roughness could have a non negligible impact on frictional pressure drops.

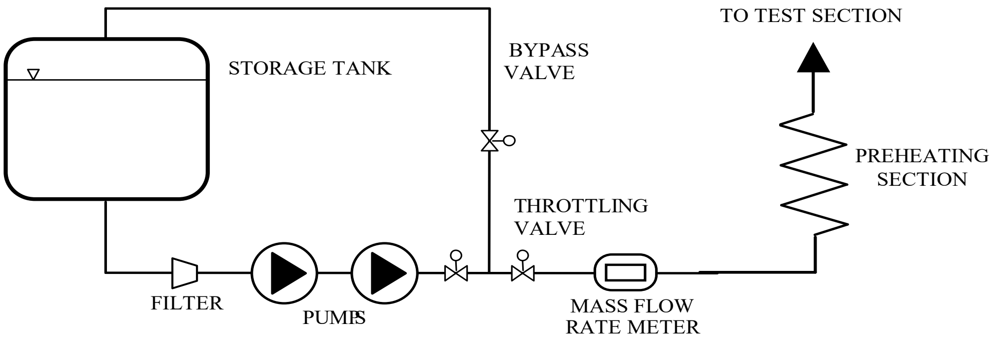
Coil diameter is 1m and coil pitch 0.79 m, resulting in a total height of the steam generator of 8m.

The test section coiled tube main data are listed in Table 3. Two identical tubes are installed in parallel for the thermalhydraulic stability investigation.

Table 3. Test section main data

Tube material	SS AISI 316
Nominal Inner diameter, d [mm]	12.53
Nominal Outer diameter [mm]	17.24
Coil diameter, D [mm]	1000
Coil pitch [mm]	800
Tube length [m]	32
Steam generator heigth [m]	8
Number of pressure taps	9
Dcoil/dtube	79.81

The facility is made by a supply section (Fig.1) and a test section (Fig.2).



(a)

(b)

Fig.1-SIET forced flow experiences supply section schematic (a), supply section pre-heater (b)

The supply section feeds demineralized water from a tank to the test section, by means of a centrifugal booster pump and a feed-water pump, i.e. a volumetric three-cilindrical pump with a maximum head of about 200 bar driven by an asynchronous three-phases motor. After the reciprocating pump a bypass line with a control valve allows the operator to impose to the circuit the desired flow rate. The bypass line is followed by a throttling valve whose scope is to introduce a strong localized pressure drop in order to avoid any eventual dynamic instability (density wave type) of the test section when it is powered.

Booster pump sucks water from a large capacity tank charged with demineralised water, with a measured mean electrical conductivity of 1.5 μS/cm, obtained with a ionic exchanger resin bed and taken from "Piacenza Levante" combined cycle thermal power station.

An electrically heated coiled tube section (pre-heater) is located beyond the flow meter, but before the test section, and allows to create the desired temperature at test section inlet in the diabatic runs and the desired quality in the adiabatic ones.

The test section (Fig. 2) is electrically heated via Joule effect by DC current. Two distinct, independently controllable and contiguous sections are provided for the single tube configuration: the first one intends to simulate the subcooling zone and the two-phase saturated zone of the steam generator, while the second the post dryout and superheating zones.

In the parallel-tube configuration, each helical coil tube is provided at inlet with a calibrated orifice (instrumented with a differential pressure transmitter) used to measure the flow rate in each channel and to visually detect the instability inception, and with a valve to impose a concentrated pressure drop (as in Fig.4). V1 and V2 in Fig.2 represent the total pressure drop (instrumented orifice + valve) introduced at the inlet of the two helical tubes, respectively.

The possibility of controlling thermal flux separately in the two zones allowed us to roughly simulate the variation in heat flux that occurs in a real once through steam generator.

For instability experiments, power was supplied only to the first section (24 m), instead the second section (8 m) worked as a riser unheated section.

Pictures of the facility are shown in Fig.3. The complete scheme of the facility, including the electrical connections for the test section and the pre heater and the valves for system control is reported in Fig.4 for both the single-tube and the parallel-tube configurations.

At the end of the plant three valves, two with automatic air operated pressure control and one manually operated, have the scope of controlling the proper pressure of the facility by throttling the mixture before it is discharged to the atmosphere.

An accurate measurement of the flow rate is obtained by a Coriolis flow-meter, having a maximum error[1] of about 0.3%, in the range of the explored flow rates.

[1] Here with the meaning of the maximum relative difference taken from calibration certificates between the measured value obtained during calibration and a "true" reference value.

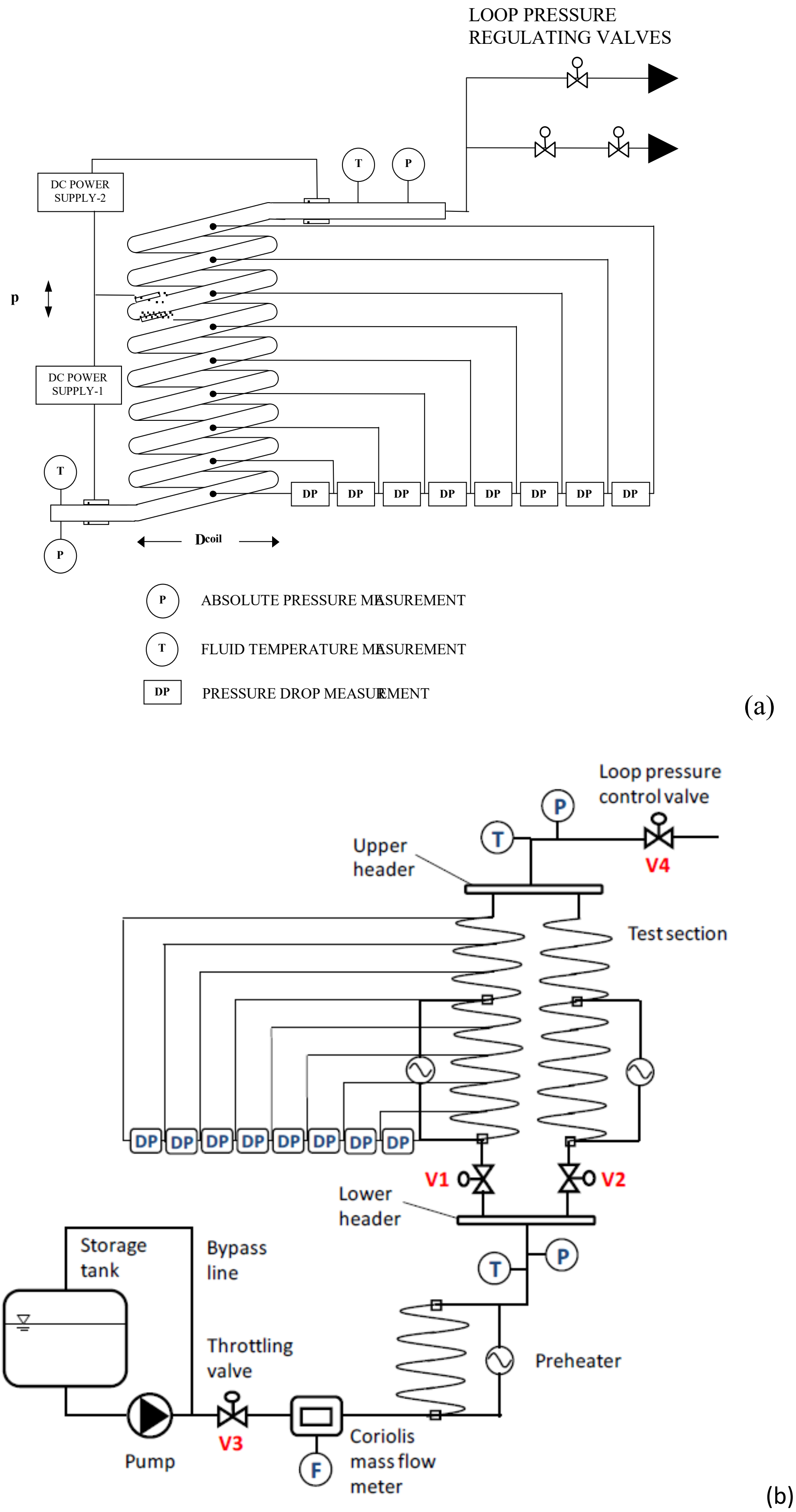
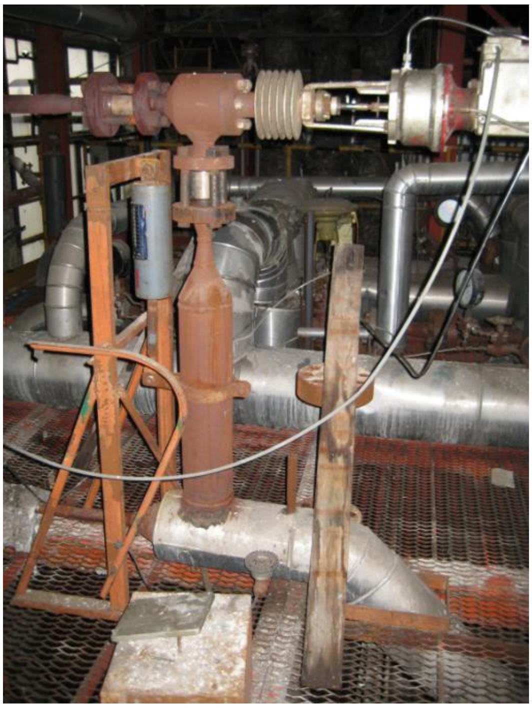
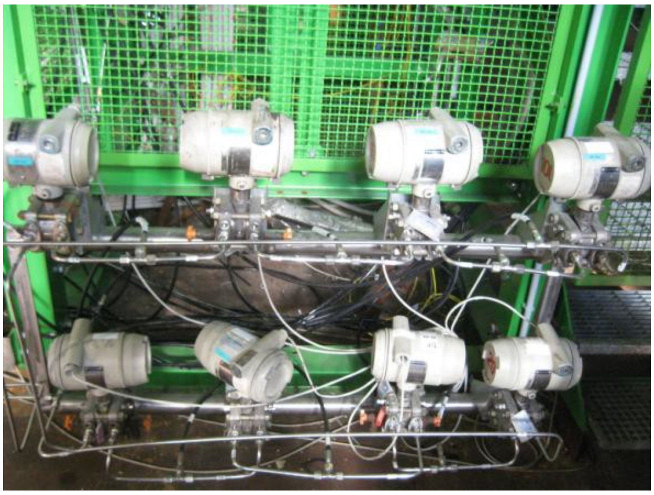


Fig.2-Helical Coil SG test facility schemes – single tube (a) and double, parallel tube (b)



Pneumatic actuator of loop pressure control valve (V4 in Fig.2b).

Calibrated orifice and channel inlet valve (V1 and V2 in Fig.2b).



Differential pressure transducers installed along channel A

Coriolis flow-meter

Fig.3-Pictures of Helical Coil Steam Generator test section

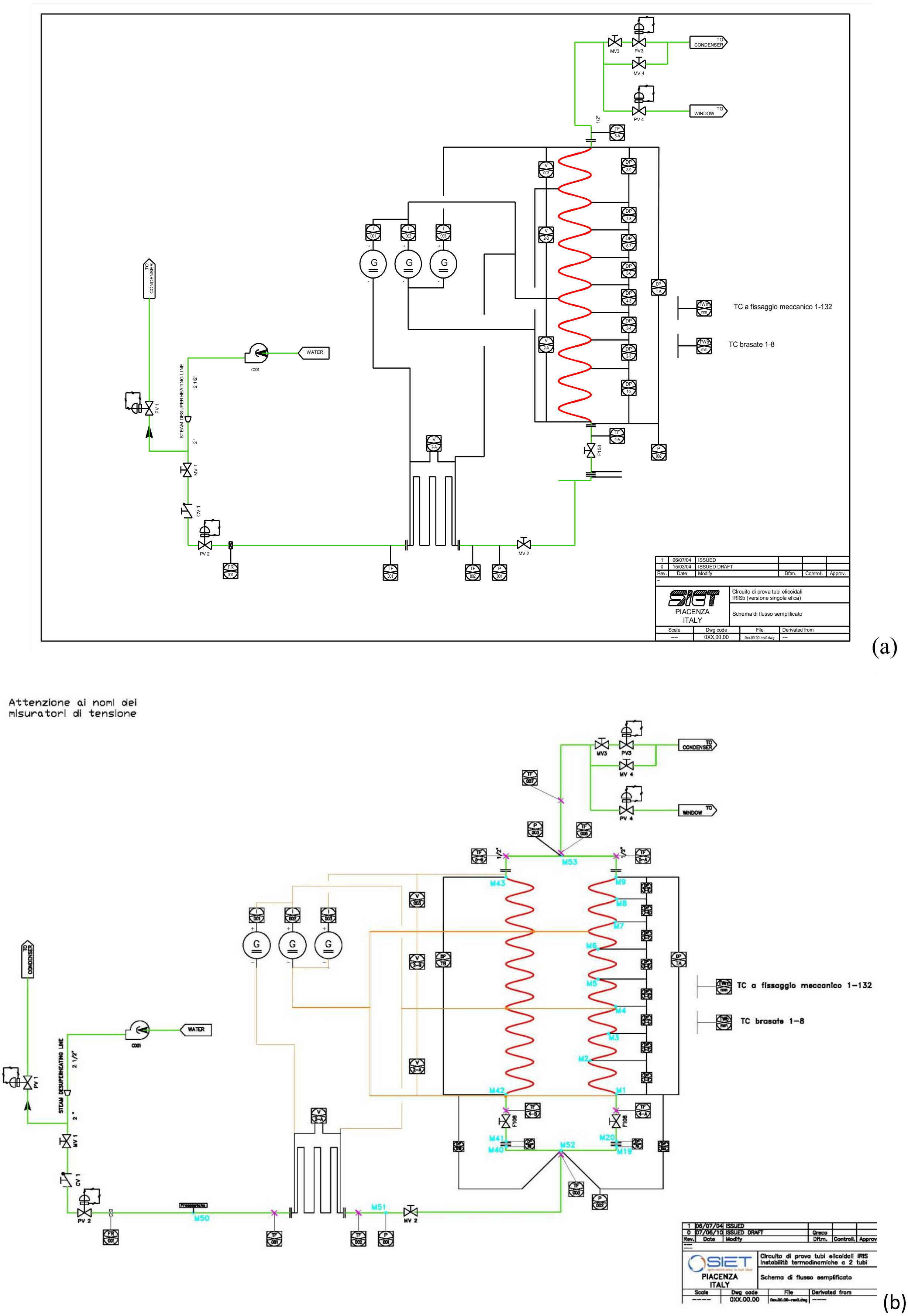


Fig.4-Helical Coils Steam generator facility: single-tube (a) and parallel-tube (b) configurations

The fluid bulk temperature is measured with a K-class thermocouple drowned in a small well, with a maximum error of about 0.6 °C in the range of the explored temperatures.

All the measurement devices have been tested and calibrated at the certified SIET labs (SIT certified).

The water absolute pressure at heating section inlet is measured by an absolute pressure transducer with a 100 bar range, and a maximum error of about 0.1%.

Nine pressure taps are disposed nearly every four meters along the coiled tube and eight differential pressure transducers (maximum error of about 0.4%) connect the pressure taps. The detailed distances between the taps are reported in Table 4.

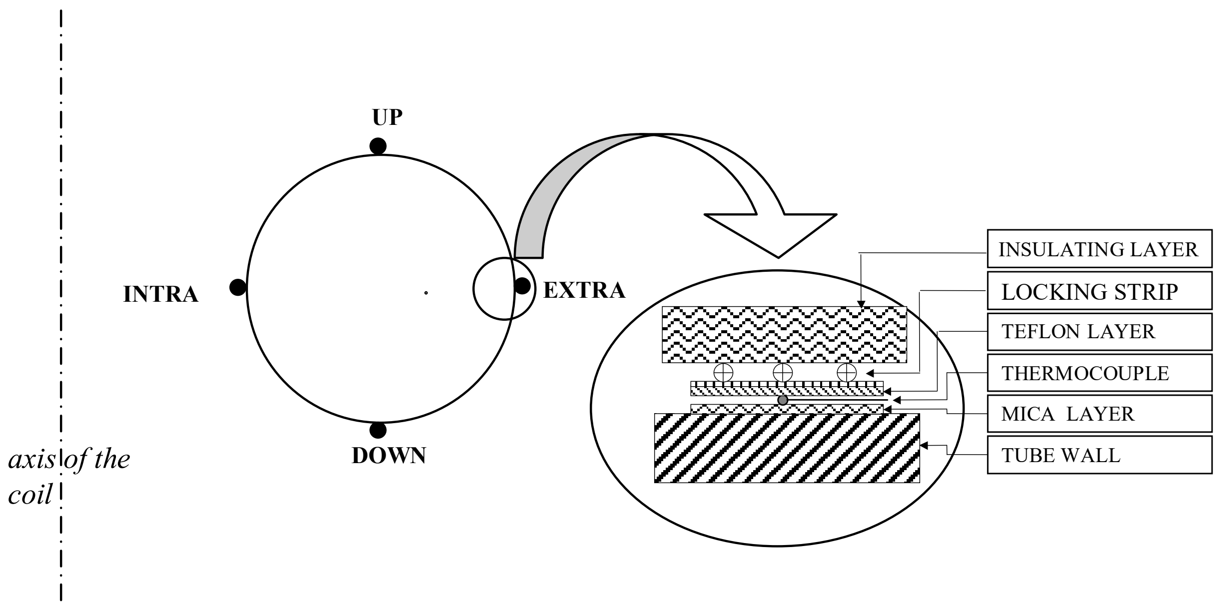
Table 4. Pressure taps distribution along the test section

	Tap 1	Tap 2	Tap 3	Tap 4	Tap 5	Tap 6	Tap 7	Tap 8	Tap 9
distance from test section inlet [mm]	200	5173	9186	13148	17141	21643	25586	29088	32059

Wall temperatures are measured with K-class thermocouples of two groups: brazed in tube wall (Thermocoax), Fig. 6 b, and manually attached on tube external wall (naked thermocouples), Fig. 6 a.

A total of 128 thermocouples have been applied: 8 are brazed and disposed in 4 groups of two opposed thermocouples (INTRA and EXTRA positions in Fig. 6); of the remaining 120 thermocouples, 116 are applied in 29 groups of 4 (INTRA, EXTRA, UP and DOWN in figure 6 a) and 4 are applied in 2 groups of 2.

A mica layer was positioned between tube wall and the thermocouple due to the necessity of maintaining thermocouple heads electrically insulated. A Teflon layer and a locking strip are applied above the thermocouples in order to jam them (for details in thermocouples calibration see appendix A of SANTINI - PhD Thesis work).



(a)

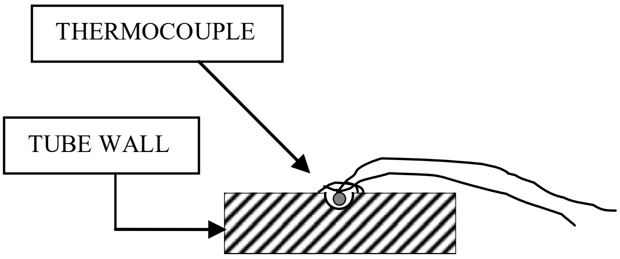


Fig.6-Schematic of manually attached thermocouples (a) and brazed thermocouples (b)

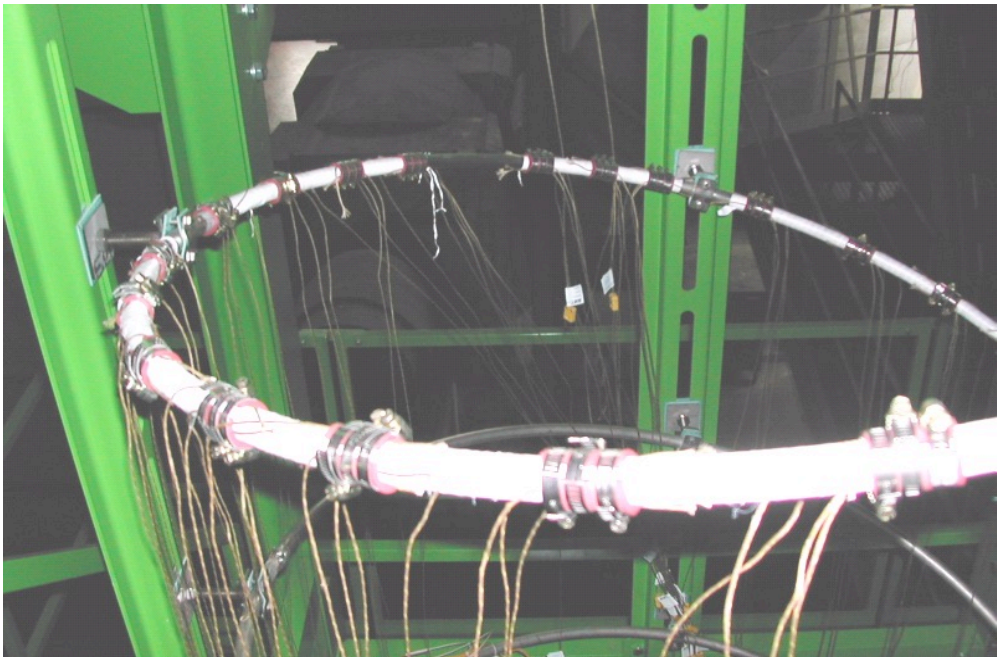
The detailed position of the thermocouples along the test section as a function of tube abscissa is reported in the Table 5.

Table 5-Thermocouples disposition along the test section

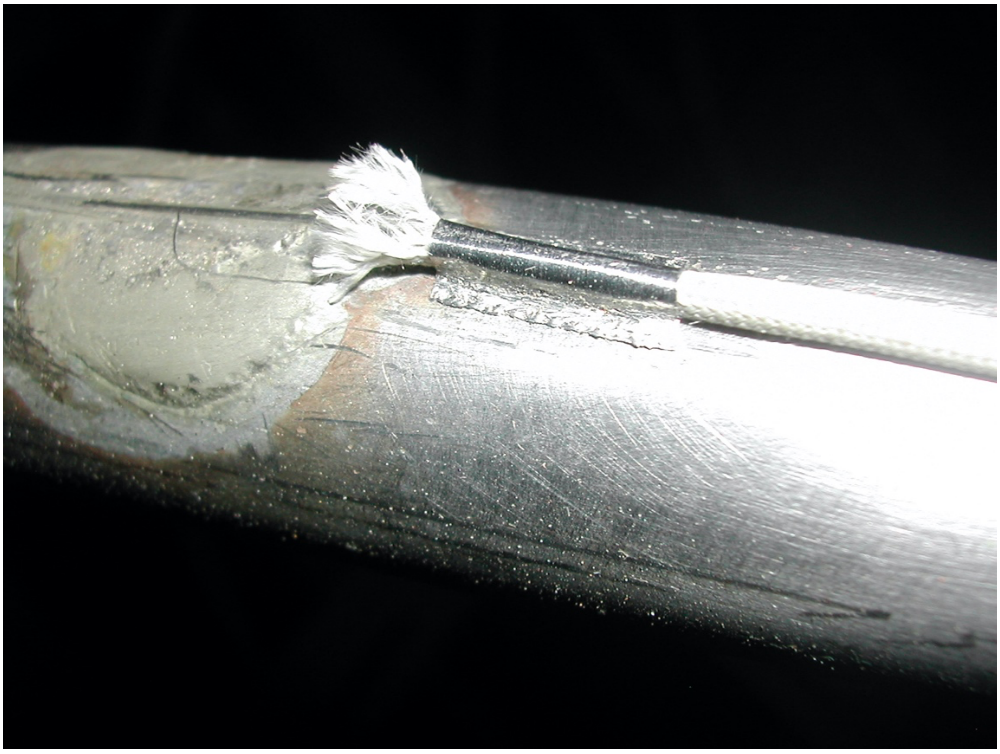
(U=UP, D=DOWN, I=INTRA, E=EXTRA; BR=brazed thermocouple)

TC-name	***Tube abscissa [mm]***	TC-name	***Tube abscissa [mm]***	TC-name	***Tube abscissa [mm]***	TC-name	***Tube abscissa [mm]***	TC-name	***Tube abscissa [mm]***	TC-name	***Tube abscissa [mm]***	TC-name	***Tube abscissa [mm]***
1E	*2191*	**7D**	*11797*	**12I-BR**	*21123*	**17D**	*23464*	**22U**	*24105*	**26E**	*24555*	**31I**	*25135*
1I	*2191*	**7I**	*11797*	**12E-BR**	*21123*	**17I**	*23464*	**22D**	*24105*	**27U**	*24665*	**31E**	*25135*
2I-BR	*4223*	**7E**	*11797*	**13U**	*21783*	**17E**	*23464*	**22I**	*24105*	**27D**	*24665*	**32U**	*25265*
2E-BR	*4223*	**8U**	*14129*	**13D**	*21783*	**18U**	*23614*	**22E**	*24105*	**27I**	*24665*	**32D**	*25265*
3U	*6194*	**8D**	*14129*	**13I**	*21783*	**18D**	*23614*	**23U**	*24205*	**27E**	*24665*	**32I**	*25265*
3D	*6194*	**8I**	*14129*	**13E**	*21783*	**18I**	*23614*	**23D**	*24205*	**28U**	*24795*	**32E**	*25265*
3I	*6194*	**8E**	*14129*	**14U**	*23074*	**18E**	*23614*	**23I**	*24205*	**28D**	*24795*	**33I-BR**	*26096*
3E	*6194*	**9U**	*16070*	**14D**	*23074*	**19U**	*23745*	**23E**	*24205*	**28I**	*24795*	**33E-BR**	*26096*
4U	*8625*	**9D**	*16070*	**14I**	*23074*	**19D**	*23745*	**24U**	*24315*	**28E**	*24795*	**34I**	*27157*
4D	*8625*	**9I**	*16070*	**14E**	*23074*	**19I**	*23745*	**24D**	*24315*	**29U**	*24915*	**34E**	*27157*
4I	*8625*	**9E**	*16070*	**15U**	*23224*	**19E**	*23745*	**24I**	*24315*	**29D**	*24915*	**35I**	*28978*
4E	*8625*	**10U**	*18231*	**15D**	*23224*	**20U**	*23825*	**24E**	*24315*	**29I**	*24915*	**35E**	*28978*
5U	*10276*	**10D**	*18231*	**15I**	*23224*	**20D**	*23825*	**25U**	*24445*	**29E**	*24915*	**36I**	*31379*
5D	*10276*	**10I**	*18231*	**15E**	*23224*	**20I**	*23825*	**25D**	*24445*	**30U**	*25025*	**36E**	*31379*
5I	*10276*	**10E**	*18231*	**16U**	*23334*	**20E**	*23825*	**25I**	*24445*	**30D**	*25025*		
5E	*10276*	**11U**	*20102*	**16D**	*23334*	**21U**	*23915*	**25E**	*24445*	**30I**	*25025*		
6I-BR	*11157*	**11D**	*20102*	**16I**	*23334*	**21D**	*23915*	**26U**	*24555*	**30E**	*25025*		
6E-BR	*11157*	**11I**	*20102*	**16E**	*23334*	**21I**	*23915*	**26D**	*24555*	**31U**	*25135*		
7U	*11797*	**11E**	*20102*	**17U**	*23464*	**21E**	*23915*	**26I**	*24555*	**31D**	*25135*		

A picture of thermocouples disposition (before thermal insulation application) in the last portion of the first part of the steam generator (@24 meters, i.e. where crisis occurs), is represented in Fig. 7(a), together with a picture of the brazed thermocouple (b).



(a)



(b)

Fig.7-Thermocouples disposition on tube wall

All the measurements are acquired by a multi-channel data acquisition system with a frequency of acquisition of 4 Hz and stored into a computer.

The steam generator tube is carefully insulated with rock wool, and the small thermal losses were previously determined with dedicated experiences and the net power given to the fluid was determined as the difference between the electrical power and the thermal losses (see appendix A of SANTINI - PhD Thesis work). These losses were measured by evaluating the flow rate and the temperature drop of hot pressurized water flowing into the steam generator and their value were correlated with the tube metal temperature (for heat losses evaluation and uncertainty analysis see appendix B of SANTINI - PhD Thesis work).

Electric power is supplied to the steam generator via Joule effect using low voltage (a hundred Volts)-high amperage current. The electric power generator is the coupling of a AC transformer, from 130 kV to 3 kV, (successively lowered to nearly 150 V for powering the test section) with a Chopper that convert alternate current into direct current2 .

Electrical power was obtained via separate measurement of current (by a shunt) and voltage drop along the test section by a voltmeter.

The uncertainty in steam generator power balances is a function of operative conditions (electric power, flow rates, pressures) and its estimation is reported in appendix A of SANTINI - PhD Thesis work.

A summary of the uncertainties is reported in Table 6.

Table 6 - List of the uncertainties of physical quantities (referred to measurement values).

Water flow rate ± 1%
Fluid bulk and wall temperature ± 0.7 °C
Absolute pressure ± 0.1%
Differential pressure ± 0.4%
Supplied electrical power ± 2.5%
Evaluated thermal losses ± 15%

[2] In reality current output is not exactly direct and a small ripple exists. This ripple slightly enhances uncertainty in electric power balance calculation (see appendix A).

2. Passive Emergency Heat Removal System

The test section at SIET labs in Piacenza is a closed loop electrically heated built with the scope of simulating the physical behavior of the passive Emergency Heat Removal System (EHRS) of IRIS reactor. IRIS EHRS structure and functioning principles are described in SANTINI - PhD Thesis work.

The experimental loop is briefly composed by a heat source, a riser, a heat sink and a downcomer (Fig.8).

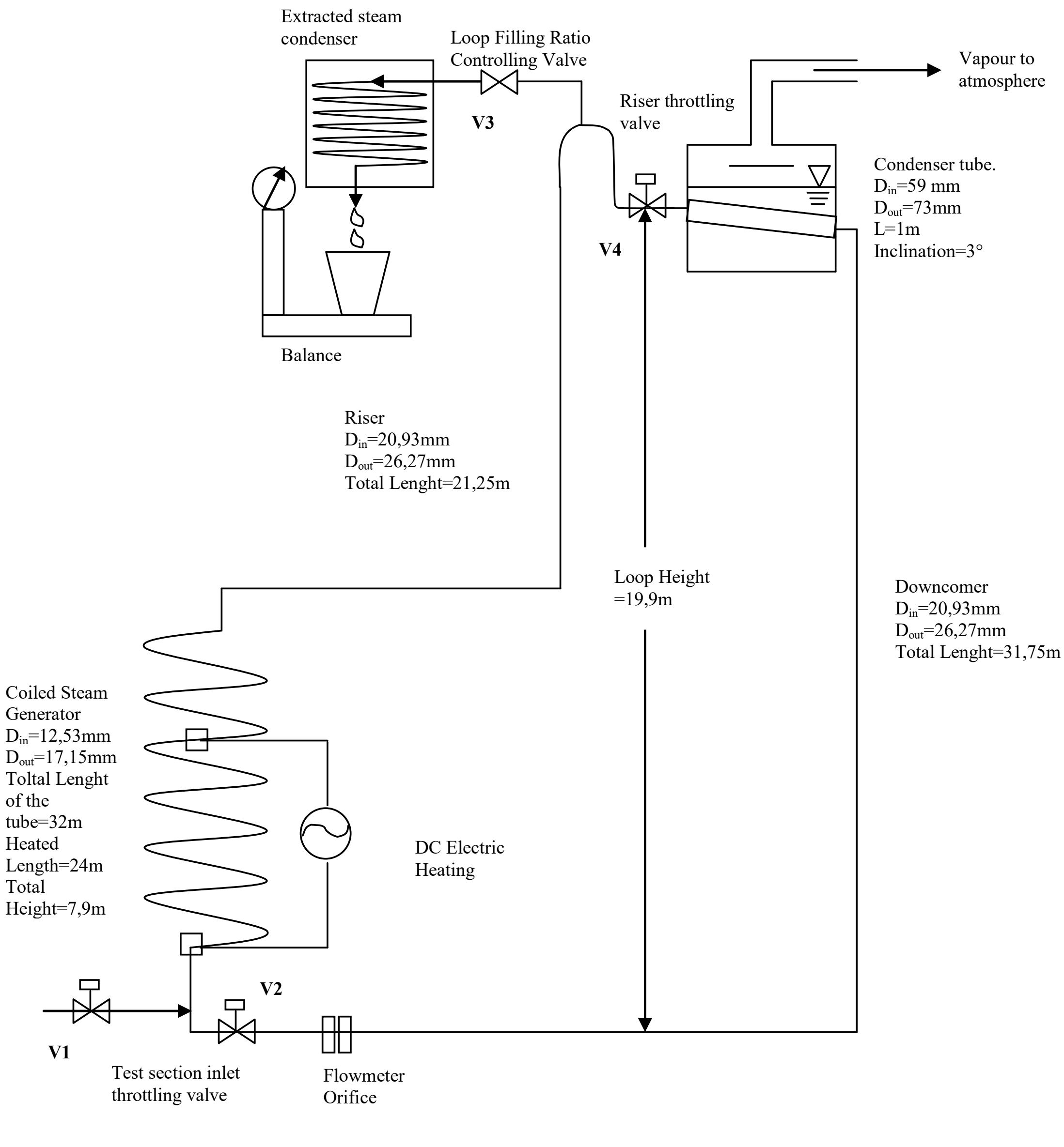


Fig.8-Scheme of the Passive Emergency Heat Removal System

The facility operates with one single pool condenser tube, 1m long with 59 and 73 mm of inner and outer diameters. The height of the experimental loop is the same of the real system (≈20 m).

The heat source is the electrically heated helical coil steam generator built for the study of two-phase pressure drops and thermal crisis. The riser is a 21.3 meters long AISI 316 stainless steel tube with an inner diameter of 20.93 mm and an outer diameter of 26.27 mm. Riser and downcomer diameters have not been scaled with respect to IRIS EHRS riser and downcomer expected pressure drops. All loop pipes were accurately insulated with rock wool. Nevertheless in a part of the experimental runs (nearly one half), the small thermal losses along riser and downcomer were compensated with an electrical wire coiled along the tubes whose power can be regulated during operation.

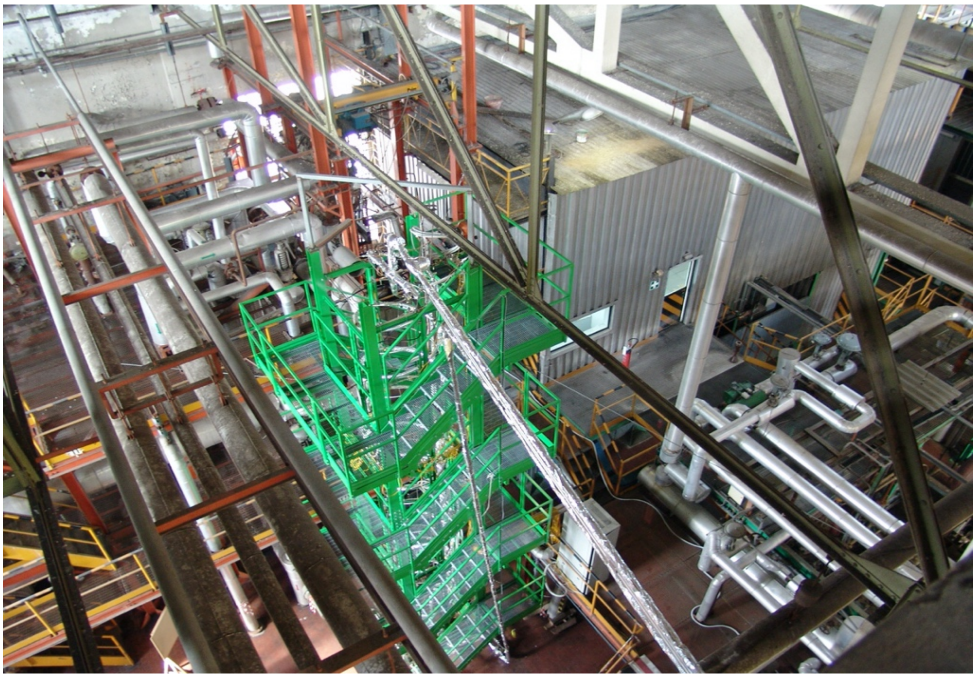


Fig.9-The steam generator (supported by the green structure) with part of the hot leg

The pool condenser (Fig.10) is submerged into a 250 liters pool. The tube of the condenser is slightly inclined (3 °) to avoid water draining during condensation. A metallic slab is placed few centimeters under the vapor escaping duct of the pool to reduce the presence of liquid droplets in the exit stream.

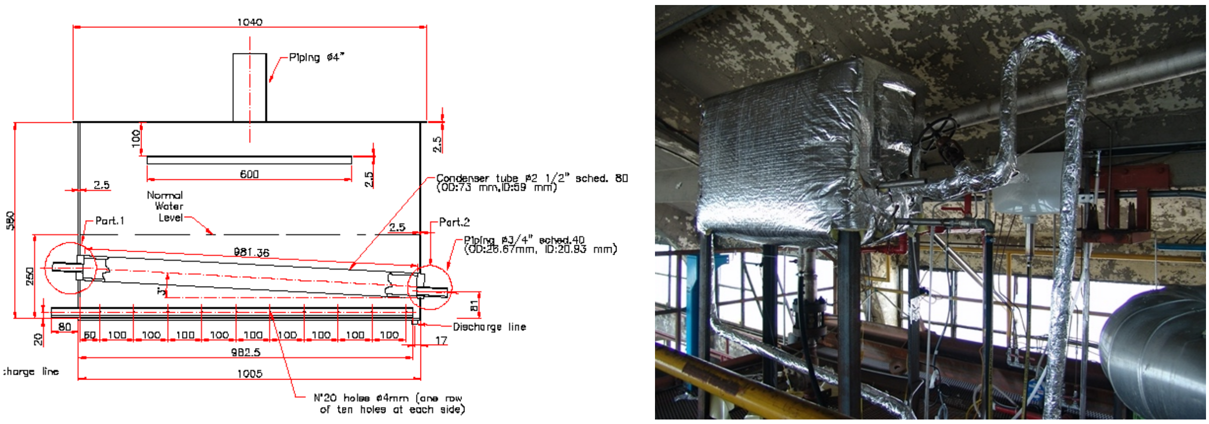


Fig.10- The pool condenser

The evaporating water in the pool is continuously replaced via a submerged drilled tube placed in the bottom of the pool. The tube in the bottom of the pool is connected to a tank whose water level is maintained to a constant value thanks to a floating device (functioning principle in Fig.11).

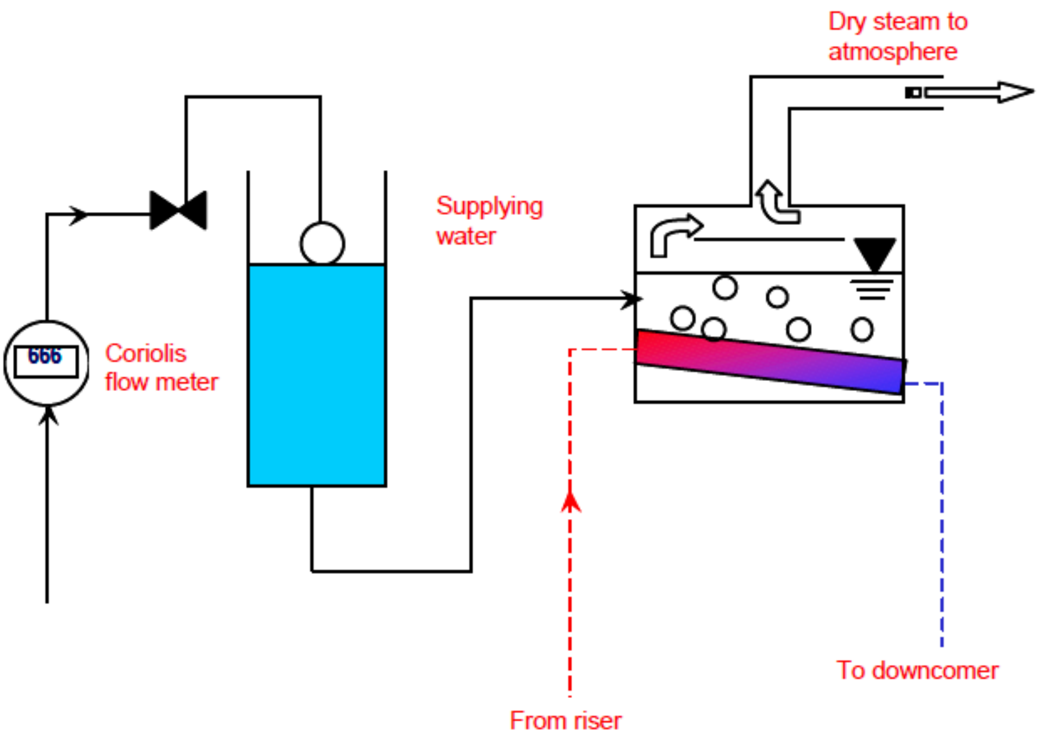


Fig.11-Pool condenser filling principle

The measured quantities in the loop (more than 200 measuring points) are flow rates, pressures (absolute and differential), temperatures and powers.

The circuit flow rate has been measured by a calibrated orifice of 5 mm placed at steam generator inlet and instrumented with a differential pressure transducer calibrated at SIET labs (SIT certified) with an estimated maximum uncertainty of 2% (see appendix C of SANTINI - PhD Thesis work).

The circuit absolute pressure is measured at steam generator inlet via an absolute pressure transducer calibrated at SIET labs and with a maximum uncertainty on read value of 0.1%.

Differential pressure transducer are placed across the throttling valves and along the downcomer with the scope of evaluating the possible presence of mixture at condenser tube outlet.

Fluid temperature measurement is obtained with K-class thermocouples (calibrated in SIET labs and with a maximum error at 100 °C of 0.4°C). Fluid temperatures are measured at steam generator inlet and outlet headers, at condenser tube inlet and outlet and inside pool condenser.

The electrical power is measured via a volt-amperometric digital instrument with a relative uncertainty guaranteed of 2.5% (for more details on uncertainties analysis see appendix C in SANTINI - PhD Thesis work).

The main geometrical characteristics of the facility are summarized in Table 7.

Table 7-IRIS EHRS test section main data

	Inner diameter [m]	Outer diameter [m]	L [m]	α [°]	R [m]
Orifice	0.01253	0.01715 (3/8'' S40)	0.56	90	0
Heated test section	0.01253	0.01715 (3/8'' S40)	24	14.3	0
Unheated test section	0.01253	0.01715 (3/8'' S40)	8	14.3	0
Upper header	0.03810	0.04826 (1.1/2'' S80)	1.10	0	0
Elbow	0.02093	0.02667 (3/4'' S40)	0.6	90	0.15
Horizontal riser	0.02093	0.02667 (3/4'' S40)	9.45	0	0
Elbow	0.02093	0.02667 (3/4'' S40)	0.2		0.15
Vertical riser	0.02093	0.02667 (3/4'' S40)	10.7	87	0
Siphon	0.02093	0.02667 (3/4'' S40)	1		0
Condenser	0.059	0.073025 (2.1/2'' S80)	1	-3	0
Elbows	0.02093	0.02667 (3/4'' S40)	3		0
Vertical downcomer A	0.02093	0.02667 (3/4'' S40)	9.45	-90	0
Elbow	0.02093	0.02667 (3/4'' S40)	0.2		0.15
Horizontal downcomer	0.02093	0.02667 (3/4'' S40)	8	0	0
Vertical downcomer B	0.02093	0.02667 (3/4'' S40)	9.23	-85	0
Elbows	0.02093	0.02667 (3/4'' S40)	2.10		0
Test section inlet header	0.02664	0.0334 (1'' S40)	1.10	0	0