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CIRTEN-POLIMI RL 1135/2010

Progettazione di una nuova facility sperimentale

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PROGETTAZIONE DI UNA NUOVA FACILITY SPERIMENTALE

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Progettazione di una nuova facility sperimentale

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INDEX

EXECUTIVE SUMMARY

Scope of the experimental research activity for the new experimental facility will be the thermohydraulic behaviour of two-phase flow mixtures into helical coil tubes of different geometries, as well as other different tube geometries (e.g. spiral tubes), enhancing and expanding the database and knowledge developed with the first, double tube but single geometry (helix diameter, tube diameter, tube inclination) test facility. The main goal is to provide a flexible and easy-to-use test facility, able to analyse different geometries test sections.

Two-phase pressure drops and dryout conditions are of paramount interest for an effective and safe design of helical coil or spiral tube steam generators and heat exchangers, as envisaged to be adopted as components and safety systems in several new generation nuclear reactors. Open literature does not offer an homogeneous and complete picture of two-phase thermohydraulic features of helically coiled heat exchangers, and also for other non conventional geometries data are limited. Several correlations devoted to frictional pressure drops are available, but their predictions are strictly confined to the limited experimental conditions explored by the various authors. No general correlations are available, as it happens for straight tubes for the prediction of two-phase frictional pressure drops.

Dryout, i.e. the rupture of the liquid film at the tube wall that occurs during flow boiling in any once through steam generator, is another two-phase flow phenomenon studied in the past for coiled tubes. With the exception of a work from Berthoud et alii [1990] into which a sort of synthesis of previous works appears, dryout has not been investigated in a wide range of thermohydraulic conditions. Even in this case, a general validity correlation is not yet available.

Moreover, the dynamic stability of the two-phase flow thermohydraulic parameters (flow rate, pressure, temperature) could be investigated as well in the new test section tube bundles. Stability maps will be identified, as a function of thermal loads and tube inlet orificing, .

The facility, operating with electrical heating on the helical coil tubes, will be upgraded in a second phase for primary fluid heating, to evaluate the behaviour of coupled primary and secondary circuits and helically coiled tube bundles.

The investigation aims at producing a complete experimental database for both two-phase pressure drops and dryout conditions, for helical coil tubes as a function of thermohydraulic and geometrical parameters:

- *Pressure*
- *Inlet subcooling*
- *Specific mass flow rate*
- *Exit quality (both at diabatic and adiabatic boundary conditions)*
- *Tube diameter*
- *Coil diameter*
- *Coil pitch*

The analysis will be carried out both at "fixed power" conditions, by means of uniform electrical heating all along the tube, and at "fixed temperature" conditions, by means of a primary fluid flow rate and corresponding system.

As far as the heating primary system is concerned, to simulate the operation in a typical PWR by avoiding complexity and cost of a 170 bar pressure vessel, the adoption of a suitable fluid (diathermic oil or molten salts) at low (environment) pressure is envisaged, able to maintain its physical properties up to PWR maximum temperature conditions (~330 °C).

1 TWO-PHASE PRESSURE DROPS

The state-of-the-art of available (open literature) thermohydraulics data for helically coil tubes is summarised in Table 1.

In recent years Chinese researchers carried out experimental campaigns supporting High Temperature Gas Reactor development, while the previous most interesting data belong to Sodium Reactor studies.

Table 1.
Helical coil, Two-phase flow pressure drop investigations

author	***fluid***	***heating***
Zhao [2003]	water	electrical
Guo [2001]	water	electrical
Huaiming [2001]	water	helium
Guo [1994]	water	N.A.
Unal [1981]	water	sodium
Chen [1981]	air-water	no heating
Ruffel [1974]	water	electrical&hot gases
Owhadi [1968]	water	electrical

As far as the geometrical parameters are concerned, i.e. tube and helical coil diameters, Fig.1 reports the range explored by past experiences.

Different from single phase flow conditions, it appears questionable and deserves to be duly investigated the importance of the coil diameter/tube diameter ratio (D/d) parameter, since the centrifugal forces in two-phase flow should act in non uniform way into the tube with respect to the tube diameter, since the steam and water fluid velocities depend on the flow regime which is strictly related to the tube diameter.

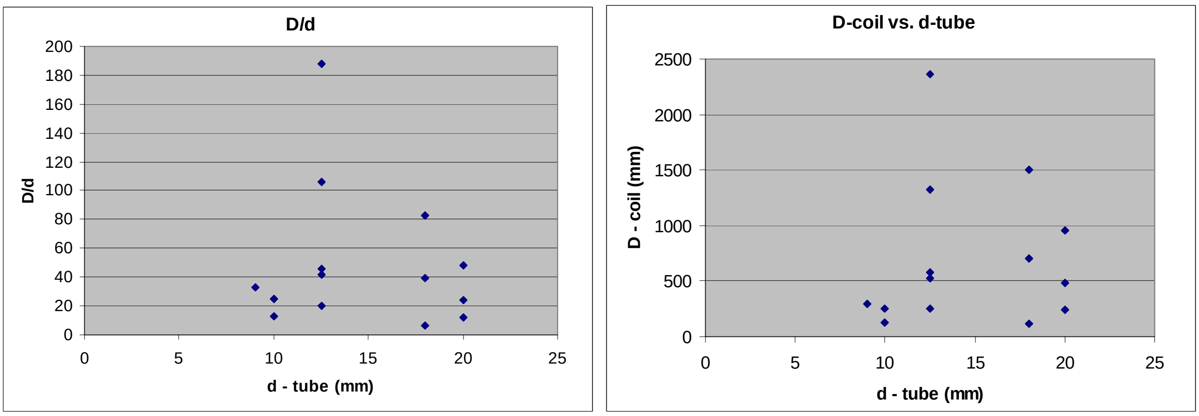


Fig. 1
Experimental set up (geometrical) data for current available open literature on two-phase pressure drops: helical coil diameter vs. tube diameter and coil diameter/tube diameter ratio.

The analysis of the available data with respect to the main thermohydraulic parameters, i.e. Pressure and Specific Mass Flow Rate versus both tube diameter and helical coil diameter, is summarised in Fig.2.

Some still unexplored areas are red-bounded, deserving investigation.

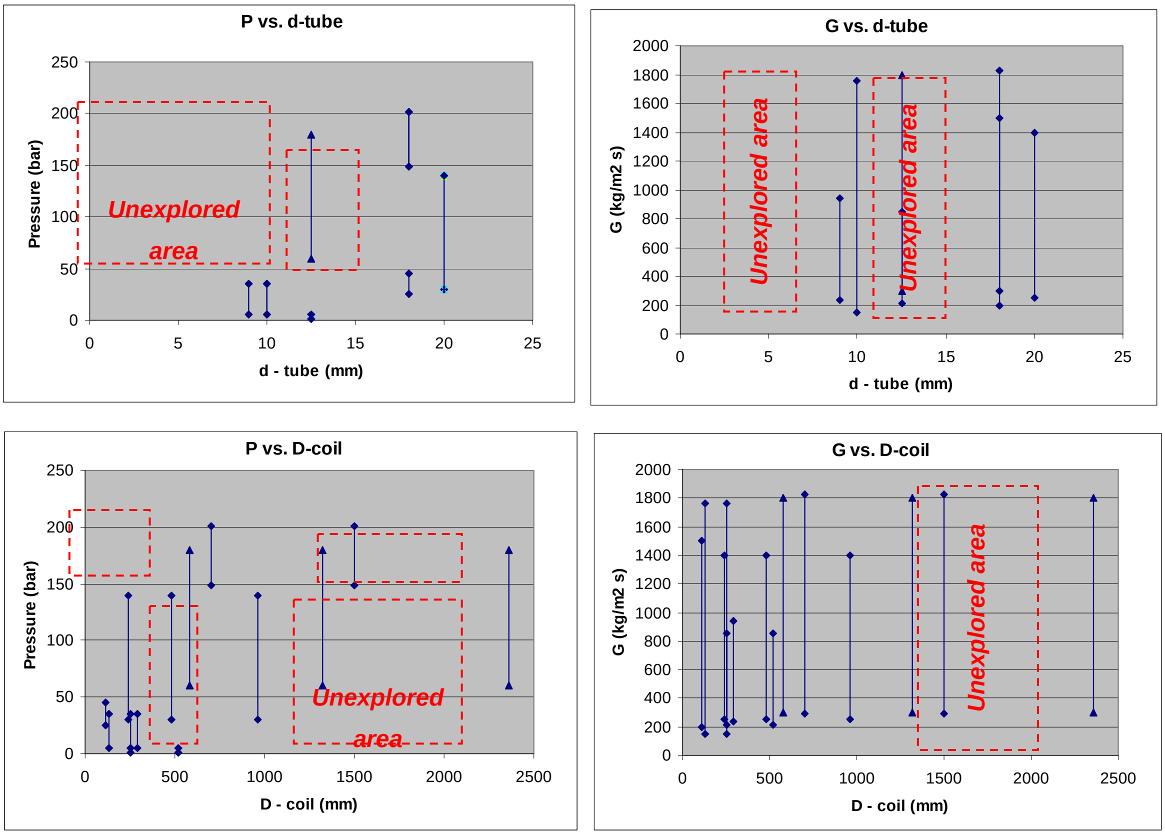


Fig. 2

Range of experimental data for fluid Pressure and Specific Mass Flow Rate in current available open literature on two-phase pressure drops, as a function of tube diameter and helical coil diameter.

Fig.3 shows the estimation of the thermal or electrical power needs, according to the experimental data of the available literature (Table 1). Both the preheater and the test section powers are reported. The total power does not exceed 1.2 MW, corresponding to Unal [1981] experimental campaign, carried out for Sodium Reactors and with large diameter (18 mm) and long tubes (40 m), large mass flux (1829 kg/m^2 s) and pressure (149 bar).

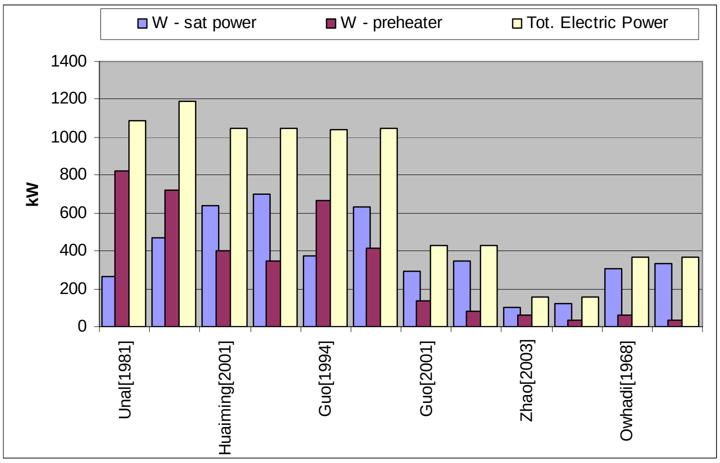


Fig. 3

Estimation of electric/thermal power values needed to reproduce available experimental data for two-phase pressure drops.

2 DRYOUT CONDITIONS

The state-of-the-art of available (open literature) data is summarised in Table 2.

No experimental campaigns have been performed in recent years on the subject. Only Unal carried out both pressure drop and dryout investigations on the same tube and helical coil geometries and thermohydraulic conditions. Other fluids than water have been investigated.

Table 2.

Helical coil, Two-phase flow dryout condition investigations

author	***fluid***	***heating***
Styrikovich [1983]	water	electrical
Breus [1983]	water	electrical
Jensen [1982]	R-113	electrical
Unal [1981]	water	sodium
Ruffel [1974]	water	Electrical&hot gases
Roumy [1971]	R12	electrical
Carver [1964]	water	electrical

The tube and helical coil diameters explored by past experiences are reported in Fig.4. The unusual very large coil diameter (beyond 3 m) refers to Carver [1964].

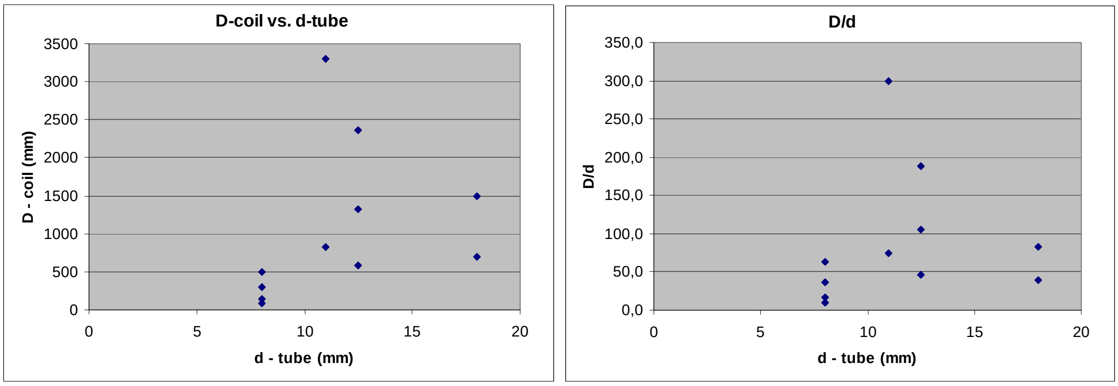


Fig. 4

Experimental set up (geometrical) data in current available open literature for two-phase dryout conditions: helical coil diameter vs. tube diameter and coil diameter/tube diameter ratio.

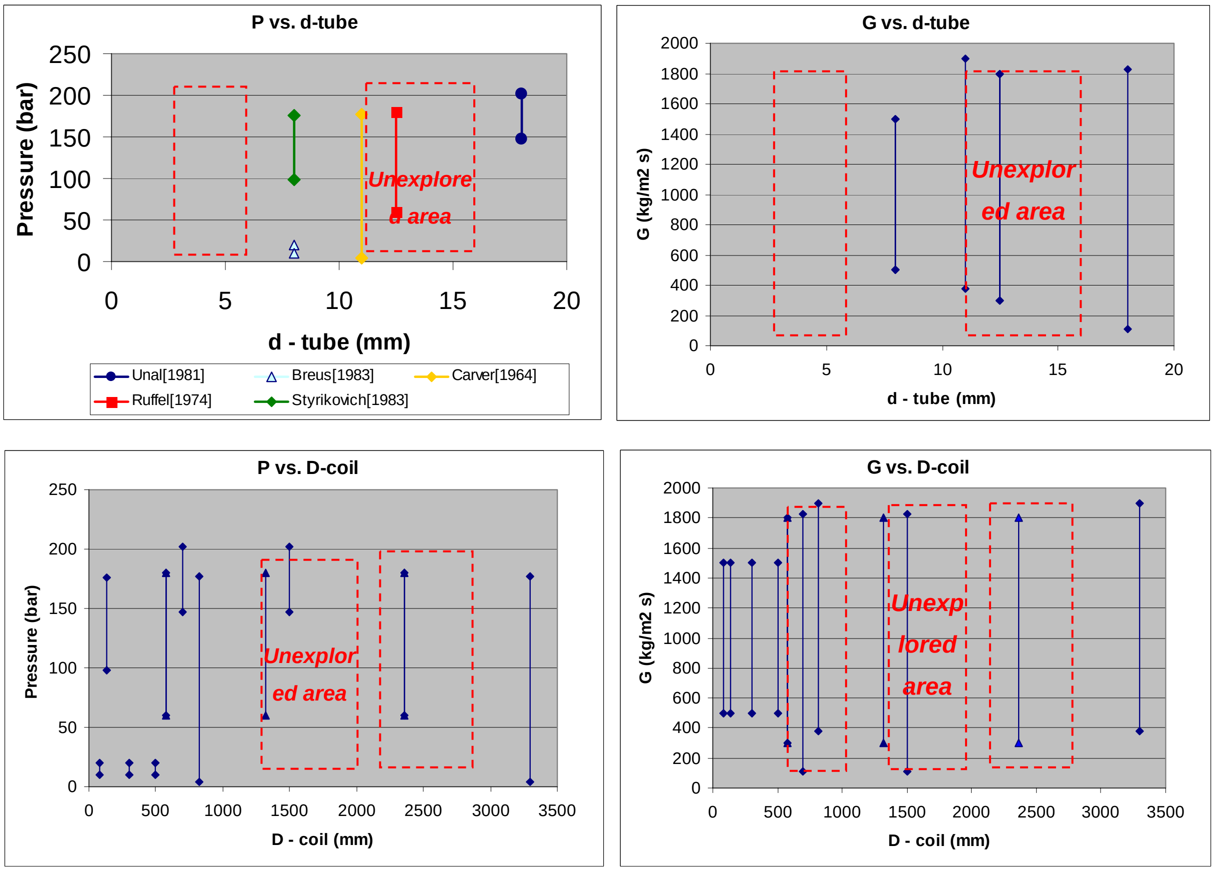


Fig. 5

Range of experimental data for fluid Pressure and Specific Mass Flow Rate in current available open literature on dryout conditions, as a function of tube diameter and helical coil diameter.

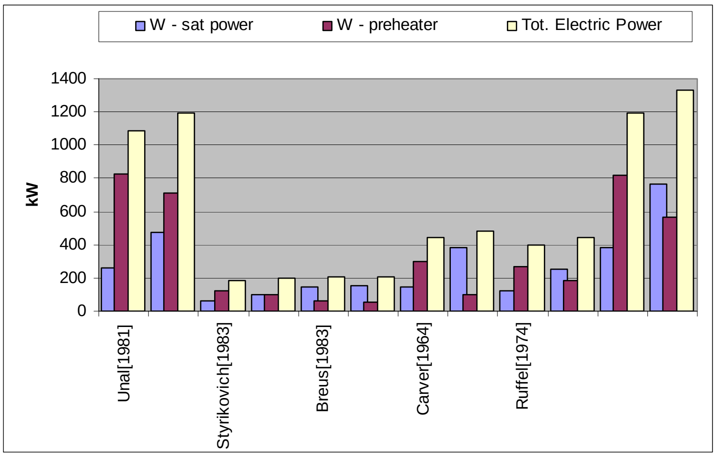


Fig. 6

Estimation of electric/thermal power values needed to reproduce available experimental data for dryout conditions.

Again, the analysis of the available data with respect to the main thermohydraulic parameters, i.e. Pressure and Specific Mass Flow Rate versus both tube diameter and helical coil diameter, is summarised in Fig.5.

Some still unexplored areas are red-bounded, deserving investigation.

Fig.6 shows the estimation of the thermal or electrical power needs, according to the experimental data of the available literature (Table 2). Both the preheater and the test section powers are reported. The total power exceeds previous limit of 1.2 MW, since Ruffel [1974] ,that adopted water as operating fluid, carried out experiments exploring the same large mass flux (1800 kg/m^2 s) adopted by Unal [1981] but at lower pressure (60 bar).

3 PRELIMINARY DESIGN – SP&DE FACILITY

The preliminary layout for the ***SP&DE*** (**S**imulation of **P**ressure drops **&** **D**ryout conditions in h**E**lical coil tubes) experimental facility is shown in Fig.8.

The facility presents a common fluid supply and pre-heater section for the investigated fluid (demineralised water), besides the "electrical heating" and the "primary fluid heating" test sections.

The main instrumentation devices (flow rates, pressure drops, fluid temperatures, tube surface temperatures) are also reported.

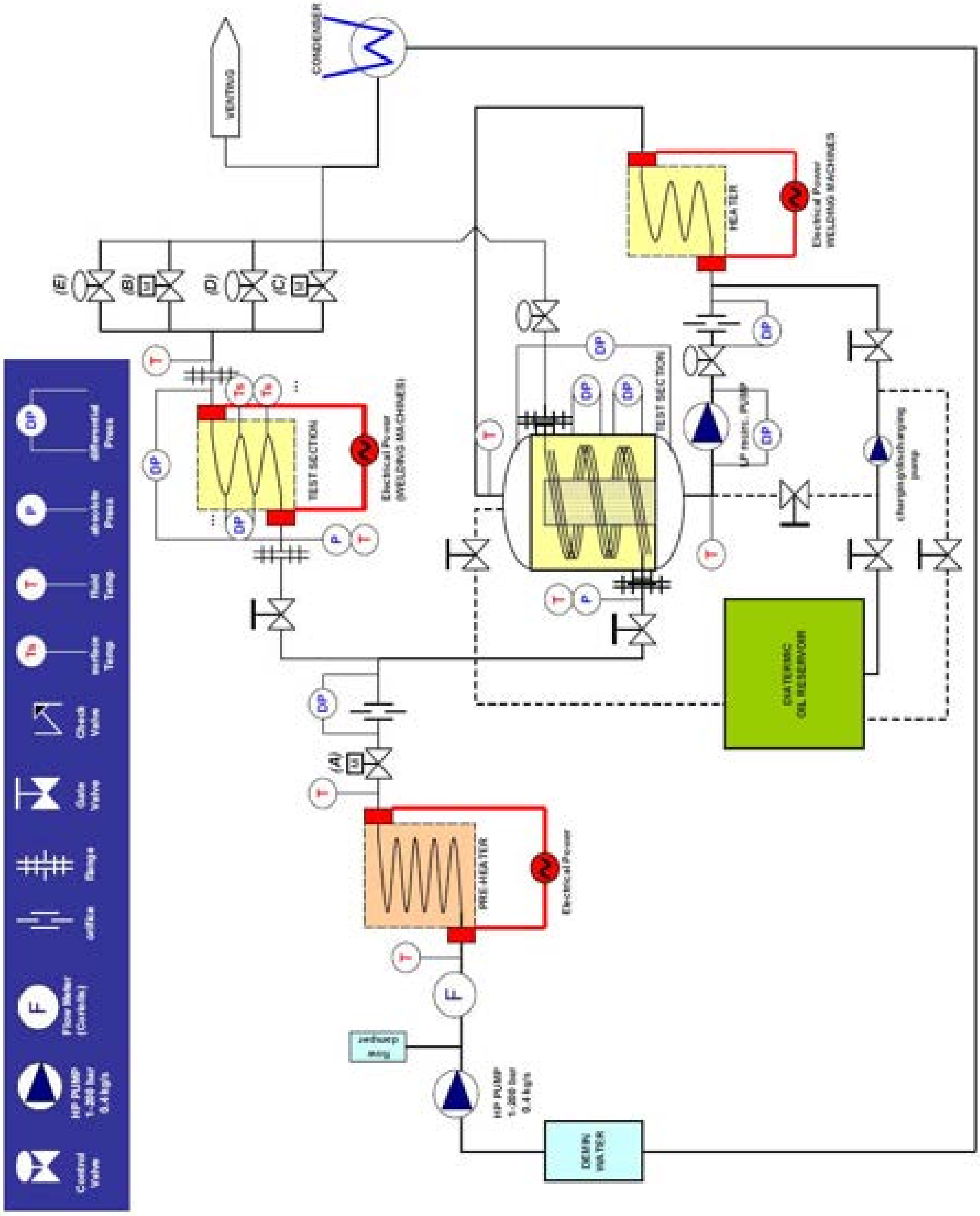


Fig. 8

Preliminary scheme of the SP&DE experimental facility

(Δp and dryout investigation, electrical and primary fluid heating).

Fig.7 shows a preliminary evaluation of the electrical and/or primary fluid heating powers, assuming the investigation ranges being:

- Pressure: 5-250 bar
- Specific mass flow rate: 200-1600 kg/m^2 s
- Exit quality: 0.1-1
- Tube diameter: 5-14 mm
- Coil diameter: 200-2000 mm

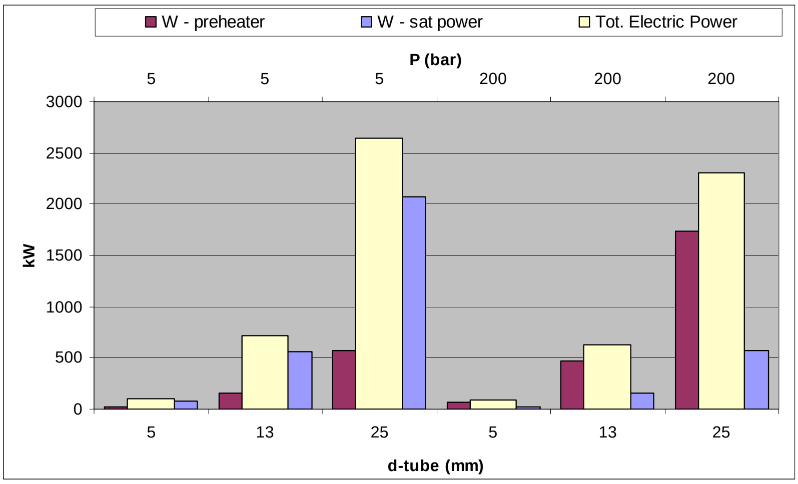


Fig. 7

Estimation of electric/thermal power values needed to explore both two-phase flow pressure drops and dryout conditions with SP&DE experimental facility.

4 DIMENSIONING & TEST MATRIX

4.1 Electrically heated test section

Main scope of the experimental campaign is to obtain a clear picture of the effects of several parameters, on two phase pressure drops and dryout conditions, in helical coils. The effects of tube diameter, coil diameter, mass flux, pressure and thermodynamic quality will be evaluated. The determination of the quality distribution in the tube, i.e. the ratio between vapour flow rate and total flow rate of the mixture, is simply determined by applying an energy balance[1], provided that the heat flux distribution along the tube is known. The simplest way to know the heat flux distribution is by applying a uniform heat flux via an electrically heating system, as performed in the electrically heated test section (Fig.9).

[1] *If the reasonable hypothesis of thermodynamic equilibrium between the phases is assumed.*

The main constrains to be fulfilled in the design of the facility are related to the availability of electrical power (both for the test section and for the preheater), as well as the maximum values of current and voltage drop across the test section.

The preheater is an electrically heated boiler with a maximum available power ($\overset{\circ}{Q}_{ph}$) of nearly 750 kW. The power for the test sections will be given by 12 DC identical welders with 250 A and 150 V of maximum current and voltage drop each (37.5 kW). All the welders can be connected in parallel (between them and with the test section) in order to give to the test section a total current of 3000 A and a maximum power ($\overset{\circ}{Q}_{ts}$) of 450 kW.

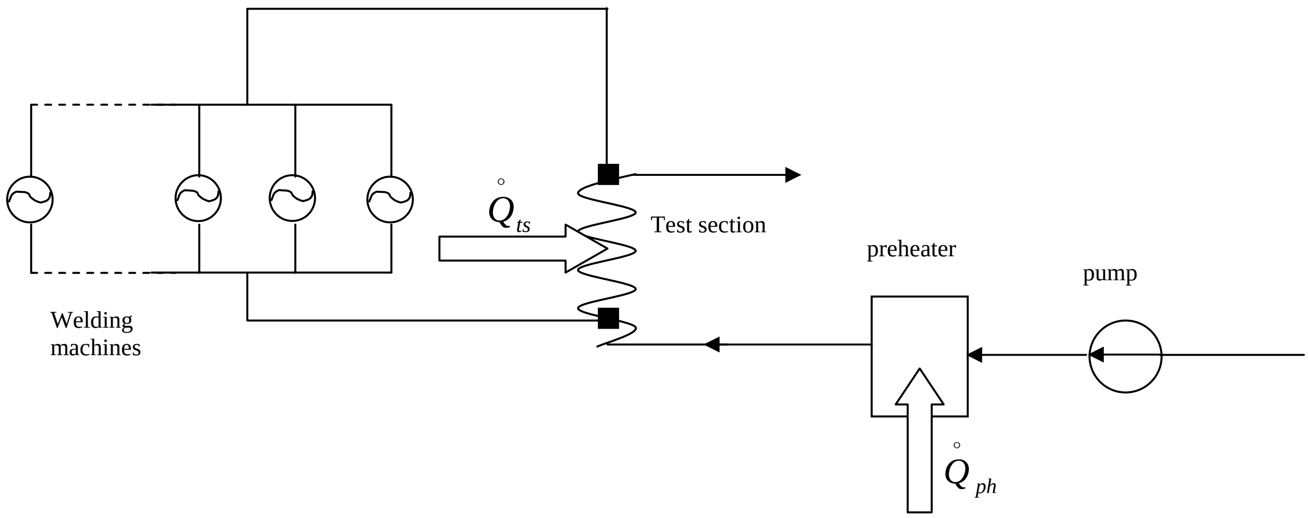


Fig. 9

Schematic of the electrically heated test section

In order to cover a wide range of experimental conditions three different tube diameters (scheduled values) and three coil to tube diameter ratios have been selected. The minimum length of each test section has been determined in order to obtain the total available power of the welders without exceeding the maximum voltage drop (150 V). Concerning the length of the tube it can be observed that, given the power to the test section, and considering a complete evaporation of the mixture (from saturated liquid to saturated vapour, in order to guarantee the dryout conditions), a long test section will lead to larger pressure drops, lower heat fluxes and a higher voltage drop. Too high pressure drops could bring problems of exceeding the maximum limits of the differential pressure taps (700 kPa). Too low heat fluxes would give problems of high thermal losses (in percentage, with respect to total power to the test section) that rise the problem on the uncertainties in the calculation of thermodynamic quality. Another problem related to low heat fluxes is due to the difficulties in the evaluation of two phase flow heat transfer coefficients, that are not one of the main aim of the campaign, but that could be obtained from the data reduction if the heat flux is sufficiently high.

On the contrary a short test section, having fixed power, mass flux and a total evaporation condition, has the negative effect of an increased importance of accelerative term in the total pressure drops that could rise some problem in data reduction. Nevertheless the test section length has been chosen with a value slightly larger then the minimum one necessary to obtain the maximum power, without exceeding the constraints on voltage drop and electrical current.

Test section diameters have been chosen in a range of reasonable values. Tubes minimum thickness has been calculated on the basis of material admissible load at full pressure and full temperature:

$$material = AISI\ 316L$$
$$P_{design} = 20\ MPa$$
$$T_{design} = 400\ °C$$
$$\sigma_a = 90\ MPa$$

According to ANSI (American National Standards Institute) rules, the tube minimum thickness is:

$$S_m = \frac{P_{design} D}{2(\sigma_a + yP)} + C \qquad (1)$$

where D is the tube external diameter, y=0.4 and C=1.27mm are safety coefficients.

Three commercially available, tube outer diameters have been selected, namely 5.48, 10.7 and 13.88 mm, hence equation (1) allows to calculate the minimum thickness and thus the proper schedule (Sched. 80 for all the pipes).

Test section helix diameter derives from the imposed relative curvature (D/d) of the test sections.

The geometrical characteristics of the selected seven final test sections are summarized in Table 3.

Table 3

Geometrical characteristics of the seven test sections for pressure drops and dryout investigations

Tube material AISI 316 L (Stainless steel)			
Tube schedule	80	80	80
Tube inner diameter_d [mm]	5.48	10.7	13.88
Tube outer diameter [mm]	10.3	17.1	21.34
Coil diameter_D [mm]	219, 438, 877	856	555, 1110, 2221
D/d	40, 80, 160	80	40, 80, 160
L/d	1000	1000	1000
L [m]	5.5	10.7	13.9
Number of coil turns	8, 4, 2	4	8, 4, 2
Number of pressure taps for each TS	5	5	5

Each test section will have a test matrix with 3 explored pressures and 4 explored mass fluxes for each pressure. Dryout conditions will be detected with thermocouples attached in the final part of the test sections. Pressure drops will be evaluated with four differential pressure transducers placed along each test section.

In order to identify a particular test section, a classification in the following will be used: TS-inner diameter-D/d. For example the first test section with a tube inner diameter of 5.48 mm and a relative curvature of 40 will be named TS-5.48-40. The group of the three test sections with inner diameter of 5.48 mm will be named TS-5.48.

The test matrix have been evaluated extending the pressure between 60 and 160 bar; maximum mass fluxes for each test section and pressure have been evaluated with the principle of not exceeding one of the following upper constraints of the facility: volumetric pump mass flow rate, welder limits (power, current, voltage drop), pressure drop between two taps.

Two experimental matrices in term of number of test sections, operative conditions and experimental procedures, will be presented in the following.

4.2 Experimental matrix

It is possible to investigate two-phase pressure drops in a tube both in diabatic and in adiabatic conditions. In the first case the electrical power is applied to the test section, evaporation occurs inside, the quality is calculated via an energy balance and the frictional term of the pressure drops is correlated with the mentioned variables of the system. In this case two fundamental advantages occur: the necessity of few runs[2] to obtain several experimental points, and the possibility of investigating thermal crisis in the same run of pressure drops investigations, thus reducing time and cost of the experiments.

In the second case, i.e. adiabatic mode, the test section is thermally insulated from heat losses and is flowed with a mixture with known quality, previously obtained in the pre-heater of the facility.

This quality must be carefully calculated by knowing pre-heater electrical power and thermal losses, both of the test and the piping.

In this second option much more runs are needed, due to the necessity of one run for each value of the quality to be investigated. With 7 test sections, 4 levels of mass flux, 3 pressures and 4 explored values for the quality, a total of 336 runs results for the adiabatic investigations and only 84 runs for the diabatic ones.

The test matrix for the **diabatic** runs, giving results both on pressure drops and on dryout, is summarized in the following tables (Tables 4, 5 and 6). The ratio between tube length and tube inner diameter has been kept constant and equal to 1000, a value slightly larger then the one needed to obtain the maximum electrical power fulfilling the constraints.

[2] *Because with many pressure taps on the test section, the complete evaporation of the mixture gives several values of quality in a single run.*

Table 4

Test matrix for diabatic runs, test sections TS-5.48 (three coil curvatures)

Test section	TS-5.48											
G [kg/m²s], Flow rate [g/s]	200, 4.7			400, 9.4			800, 18.9			1600, 37.7		
P [bar]	60	100	160	60	100	160	60	100	160	60	100	160
Preheater power [kW]	5	6	7	10	11	13	19	22	26	38	45	52
TS power [kW]	8	7	7	16	14	14	32	28	28	65	56	56
TS current [A]	343	319	319	486	451	451	687	638	638	971	903	903
TS voltage drop [V]	24	22	19	33	31	27	47	44	39	67	62	55
Estimated max. pressure drop[3] [kPa]	3	2	1	13	7	4	51	28	14	202	112	57
Thermal flux [kW/m²]	86	74	57	172	149	114	344	297	229	688	594	458

Table 5

Test matrix for diabatic runs, test section TS-10.7 (one coil curvature)

Test section	TS-10.7											
G [kg/m²s], Flow rate [g/s]	200, 18			400, 36			800, 72			1600, 144		
P [bar]	60	100	160	60	100	160	60	100	160	60	100	160
Preheater power [kW]	18	21	25	37	43	50	73	86	99	146	171	198
TS power [kW]	31	27	27	62	53	53	124	107	107	247	214	214
TS current [A]	734	682	682	1038	964	964	1468	1364	1364	2076	1929	1929
TS voltage drop [V]	42	39	34	60	55	49	84	78	69	119	111	97
Estimated max. pressure drop[4] [kPa]	3	2	1	11	6	3	45	25	13	179	99	51
Thermal flux [kW/m²]	86	74	57	172	149	114	344	297	229	688	594	458

[3] *For one pressure drop transducer.*

[4] *For one pressure drop transducer.*

Table 6

Test matrix for diabatic runs, test section TS-13.88 (three coil curvatures)

Test section	TS-13.88											
G [kg/m²s], Flow rate [g/s]	200, 30			400, 60			800, 120			1600, 240		
P [bar]	60	100	160	60	100	160	60	100	160	60	100	160
Preheater power [kW]	31	36	42	62	72	83	123	144	167	246	288	334
TS power [kW]	52	45	45	104	90	90	208	180	180	416	360	360
TS current [A]	1016	944	944	1437	1335	1335	2032	1888	1888	2873	2670	2670
TS voltage drop [V]	51	48	42	72	67	59	102	95	84	145	135	118
Estimated max. pressure drop[5] [kPa]	3	1	1	11	6	3	43	24	12	171	95	48
Thermal flux [kW/m²]	86	74	57	172	149	114	344	297	229	688	594	458

The test matrix for the **adiabatic** runs, giving information only on pressure drops, is summarized in the following tables (Tables 7, 8 and 9). Four different values for the quality have been selected and, as in the previous matrix, 4 mass fluxes and 3 pressures are adopted.

Table 7

Test matrix for adiabatic runs, test section TS-13.88 (three coil curvatures)

Test section		TS-5.48											
G[kg/m²s], Flow rate[g/s]		200, 4.7			400, 9.4			800, 18.9			1600, 37.7		
	P[bar]	60	100	160	60	100	160	60	100	160	60	100	160
Quality	Power[6][kW]	7	8	9	14	15	17	27	31	35	55	62	70
0.1	DP[7][kPa]	0.7	0.5	0.4	2.9	2.0	1.6	11.4	8.0	6.4	45.7	32.1	25.5
Quality	Power [kW]	8	9	10	17	18	19	34	36	39	68	73	78
0.3	DP [kPa]	2.2	1.3	0.8	8.7	5.2	3.2	34.6	20.9	13.0	138.4	83.5	51.8
Quality	Power [kW]	11	11	11	22	22	22	44	45	45	88	89	89
0.6	DP [kPa]	4.6	2.6	1.5	18.5	10.5	5.8	74.0	42.2	23.2	296.1	168.8	92.8
Quality	Power [kW]	13	13	13	27	26	25	54	53	50	107	106	101
0.9	DP [kPa]	4.4	2.5	1.3	17.8	9.9	5.2	71.1	39.7	20.7	284.4	158.7	82.9

[5] *For one pressure drop transducer.*

[6] *Power to electrical pre-heater, assuming 10% thermal losses.*

[7] *Estimated pressure drops for every pressure drop transducer along the test section.*

Table 8

Test matrix for adiabatic runs, test section TS-10.7 (three coil curvatures)

Test section		TS-10.7											
G[kg/m²s], Flow rate[g/s]		200, 18			400, 36			800, 72			1600, 144		
	P[bar]	60	100	160	60	100	160	60	100	160	60	100	160
Quality	*Power [kW]*	26	29	33	52	59	67	105	118	133	209	236	267
0.1	*DP [kPa]*	0.6	0.4	0.3	2.5	1.8	1.4	10.0	7.0	5.6	40.0	28.1	22.3
Quality	*Power [kW]*	32	35	37	65	69	74	130	139	148	259	277	296
0.3	*DP [kPa]*	1.9	1.1	0.7	7.6	4.6	2.8	30.3	18.3	11.3	121.1	73.0	45.3
Quality	*Power [kW]*	42	42	43	83	85	85	167	170	170	334	340	340
0.6	*DP [kPa]*	4.0	2.3	1.3	16.2	9.2	5.1	64.7	36.9	20.3	259.0	147.6	81.2
Quality	*Power [kW]*	51	50	48	102	101	96	204	201	192	408	402	385
0.9	*DP [kPa]*	3.9	2.2	1.1	15.5	8.7	4.5	62.2	34.7	18.1	248.8	138.9	72.5

Table 9

Test matrix for adiabatic runs, test section TS-13.88 (three coil curvatures)

Test section		TS-13.88											
G[kg/m²s], Flow rate[g/s]		200, 30			400, 60			800, 120			1600, 240		
	P[bar]	60	100	160	60	100	160	60	100	160	60	100	160
Quality	*Power [kW]*	44	50	56	88	99	112	176	198	224	353	396	449
0.1	*DP [kPa]*	0.6	0.4	0.3	2.4	1.7	1.3	9.5	6.7	5.3	37.9	26.6	21.1
Quality	*Power [kW]*	55	58	62	109	117	125	218	233	249	436	467	499
0.3	*DP [kPa]*	1.8	1.1	0.7	7.2	4.3	2.7	28.7	17.3	10.8	115.0	69.3	43.0
Quality	*Power [kW]*	70	71	72	140	143	143	281	286	286	562	572	573
0.6	*DP [kPa]*	3.8	2.2	1.2	15.4	8.8	4.8	61.5	35.0	19.3	245.8	140.1	77.1
Quality	*Power [kW]*	86	85	81	172	169	162	344	339	324	687	677	647
0.9	*DP [kPa]*	3.7	2.1	1.1	14.8	8.2	4.3	59.0	33.0	17.2	236.2	131.8	68.8

The diabatic runs and the adiabatic ones will furnish results on two-phase pressure drops that, in principle, will not be identical. The comparison between the two set of results will allow us to determine the effect of heat flux on two-phase pressure drops in order to evaluate its importance.

The total number of runs is 420 (84+336) and *if* it will be difficult to implement due to limitations in time and budget, we propose a reduced test matrix in the following.

4.3 A Reduced program experimental matrix

In order to reduce the total number of runs, a reduced test matrix including 4 test sections (instead of 7), 2 pressures, 3 mass fluxes and 4 qualities has been prepared. For such a purpose the following values are selected:

Test sections: TS-10.7-40, TS-10.7-80, TS-10.7-160, TS-13.88-80

G= 200, 800, 1600

P= 60, 160

x= 0.1, 0.3, 0.6, 0.9

resulting in a total number of runs of 120 (24 for the diabatic ones and 96 for the adiabatic ones). This test matrix is a subsystem of the previously shown.

4.4 Fluid heated test section

The fluid heated test section will simulate the primary circuit of a power plant, in which thermal power is generated and transferred from a heat source (the heating elements) to a heat sink (through the steam generator). A diathermic oil (SYLTHERM 800) has been selected as primary fluid, due to its capacity to reach high temperatures (max 400 °C) with no need for high pressurization. Cost, availability and problems in case of water/oil mixing must be taken into account. The only degree of pressurization for the circuit is due to the small vapour tension of SYLTHERM 800 (Fig. 10) and to the need of overcoming the frictional pressure drops due to oil circulation.

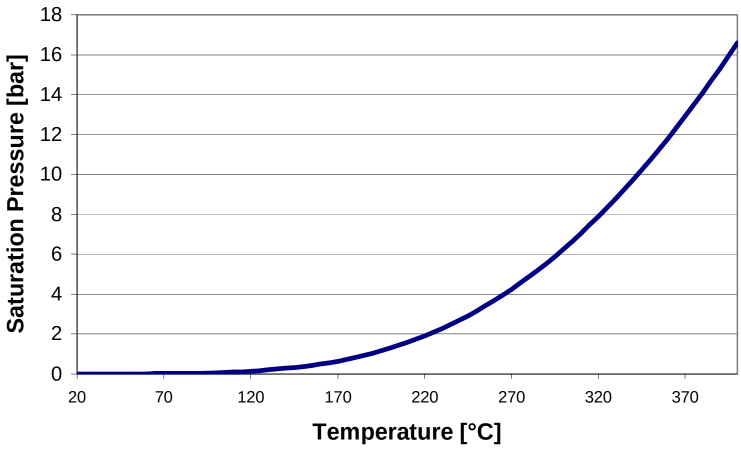


Fig. 10

Vapour Saturation Pressure of SYLTHERM 800 diathermic oil

A simplified sketch of the primary circuit is reported in the following figure (Fig. 11).

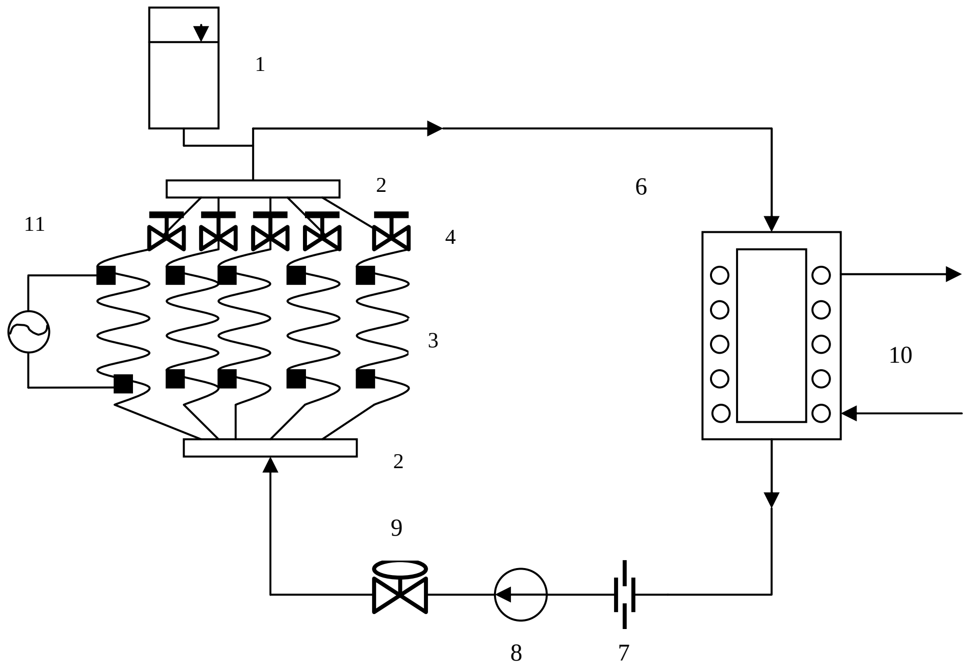


Fig. 11

Oil circuit scheme: 1-Pressurizer, 2-Heaters headers, 3-Heaters, 4-Heaters gate valves, 6-steam generator, 7-Calibrated orifice (flow meter), 8-Oil circulating pump, 9-Flow rate control valve, 10-Secondary side, 11-Electrical Welders

4.4.1 Oil heaters

Oil heaters represent the heat source of the primary circuit and have the same function of fuel elements in a nuclear power plant. A configuration of several parallel electrically heated steel tubes with oil flowing inside has been selected.
The choice of tube dimensions and number for oil heaters is a compromise between different goals on electric heating, pressure drops and maximum oil temperature at wall. Long tubes can guarantee low thermal fluxes and low oil wall-temperatures, but will rise problems of circuit pressure drops (hence problems of pump cost and availability). Large tube diameters will give low pressure drops but low electrical resistance that brings problems of too high currents in the conductors. The number of tubes is another varying parameter.
For the heating elements (number 2 in Figure 12), 6 parallel tubes, helicoidally shaped, electrically heated and with the oil flowing inside have been selected.

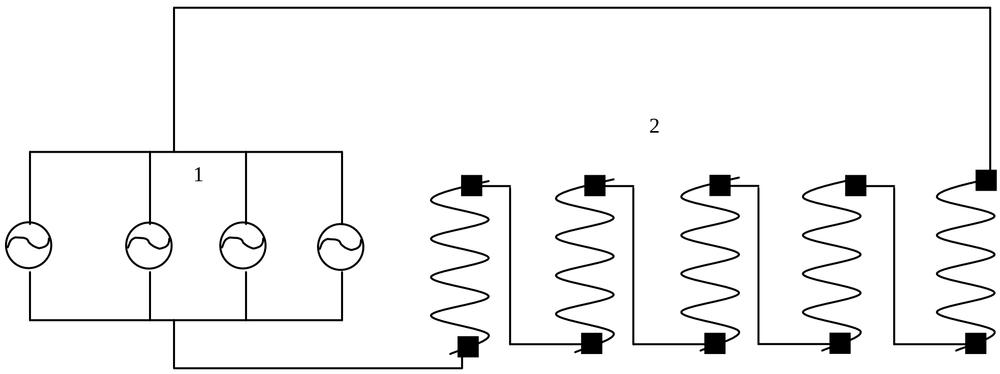


Fig. 12

Schematic of welders electrical connection to the heaters: 1-Welders, 2-Heaters

The electrical connection between the welders is schematised in Fig.12, all the welders are connected in parallel and all the heaters are electrically connected in series. The maximum value of electrical current for the 12 welders available is 3000 A and the maximum overall voltage drop is about 150 V. By fixing the tube number and diameter, the length of each tube is automatically determined because of the electrical constraints necessary to obtain the maximum available power.

The geometrical characteristics for the heating tubes are summarized in Table 10.

Table 10

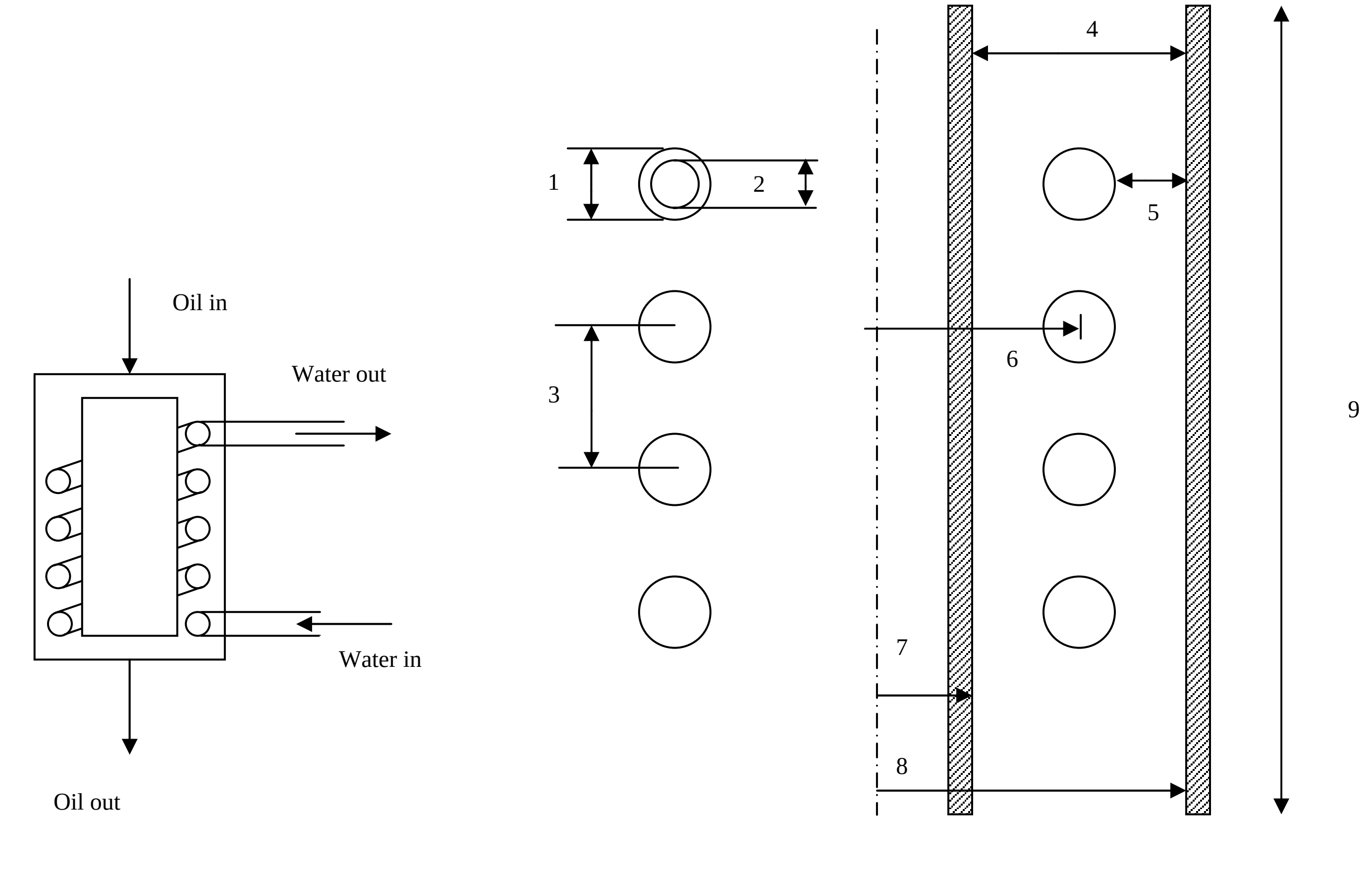
Dimensions of oil heaters

Number of parallel tubes	Material	Tube schedule	Tube length [m]	Inner diameter [mm]	Outer diameter [mm]	Helix diameter [m], number of coils for each tube
6	SS AISI 316	40	5.3	40.9	48.26	0.5, 3.4

A common header collects the oil from each heating tube and a pipe brings the oil to the steam generator. The estimation for the overall length of the piping (from the heating section to the test section and viceversa) is 20 m, with piping 88.9 mm outer diameter and 82.14 mm inner diameter. The two headers are 1 m length, 107.5 mm and 114.3 mm inner and outer diameter respectively.

4.4.2 Steam generator

The steam generator is an helically coiled tube set into an annular space in which the oil exchange the thermal power in a cross flow layout (Figure 13).



(b)

(a)

Fig. 13

The steam generator (SG) working principle (a) and detailed layout (b): 1-tube outer diameter, 2-tube inner diameter, 3-tube pitch, 4-gap, 5-throat, 6-helix diameter, 7-gap inner diameter, 8-gap outer diameter, 9-SG height.

Particular care will be necessary in designing the gaps between the SG pipe and the annulus wall, and the pitch/tube diameter ratio to ensure proper external convective coefficients with an high viscosity and low thermal conductivity fluid such as a diathermic oil.

Some difficulties could rise in the application of tube wall thermocouples due to the proximity of oil thermal boundary layer that could influence the temperature measurement.

A possible layout of the steam generator is the following:

tube inner diameter:	d_{in}= 12.53 mm
tube outer diameter:	d_{out}= 17.11 mm
coil diameter:	D_c= 0.6 m
tube length:	L_t= 32 m
number of coils:	N_c= 17
pitch/diameter ratio:	P/D= 2.5
SG height:	0.7 m
gap:	22 mm
throat:	2.5 mm
gap inner diameter:	589 mm
gap outer diameter:	611 mm

With an oil (SYLTHERM 800) flow rate of 15 kg/s and oil inlet temperature of 315 °C, the primary mean convective coefficient would be of 5 kW/m^{2}K for a total bundle pressure drop of 56 kPa.

4.4.3 Pressurizer

A pressurizer/oil damper of about 85 litres completes the circuit, to allow the thermal expansion of the oil from cold to hot operation and to damp overpressures related to rapid flow excursions.

Dimensions of the pressurizer depends mainly on the following factors: oil inventory of the circuit, temperature maximum excursions and maximum allowable pressure.

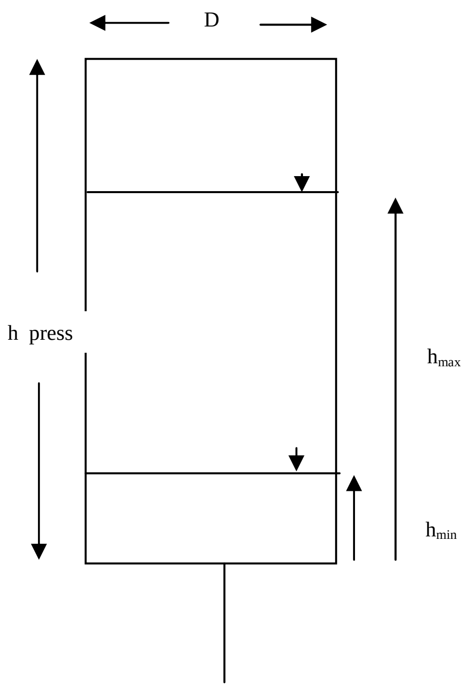


Fig. 14

Pressurizer scheme

For a conservative design, the air (or N_2) compression in the pressurizer is assumed adiabatic[8], thus the following law is applicable:

$$p_0 V_0^{\gamma} = p_{\max} V_{\max}^{\gamma} \rightarrow \frac{p_{\max}}{p_0} \equiv \delta = \left(\frac{V_0}{V_{\max}} \right)^{\gamma} \qquad (2)$$

where $p_{\max}$ is the maximum allowable pressure for the circuit, p_0 is the atmospheric pressure, V_0 is the volume occupied by air in the pressurizer when at minimum oil level ($h_{\min}$) and $V_{\max}$ is the volume occupied by air in the pressurizer when at maximum oil level ($h_{\max}$):

$$V_0 = \pi \frac{D^2}{4} (h_{press} - h_{\min}) \qquad (3), \text{ and}$$

$$V_{\max} = \pi \frac{D^2}{4} (h_{press} - h_{\max}) \qquad (4)$$

and imposing that the minimum level is a fraction (α , 0<α <1) of the total height of the pressurizer:

$$h_{\min} = \alpha \cdot h_{press} \qquad (5)$$

combining Eqs.(2) to (5):

$$\delta^{1/\gamma} = \frac{h_{press}(1-\alpha)}{h_{press} - h_{\max}} \qquad (6)$$

The maximum level of the pressurizer is related to the minimum level via the total inventory of oil that must be stored in the pressurizer:

$$\pi \frac{D^2}{4} (h_{\max} - h_{\min}) \rho_{oil}^{20°C} = \Delta M \qquad (7)$$

so that it is possible to write:

[8] *Due to the slow variations of pressure, an isothermal compression would be more realistic.*

$$h_{\max} = \frac{4\Delta M}{\pi D^2 \rho_{oil}^{20^\circ C}} + h_{\min} \equiv \beta + h_{\min} = \beta + \alpha \cdot h_{press} \qquad (8)$$

Combining relation (8) with previously obtained relation (6):

$$h_{press} = \frac{\beta \cdot \delta^{1/\gamma}}{(1-\alpha)(\delta^{1/\gamma} - 1)} \qquad (9)$$

The last equation allows to determine the vertical dimension of the pressurizer having selected its diameter, the maximum pressure for the circuit and a reasonable value for the minimum oil level in the tank.
By making the following assumptions:

-circuit oil inventory at 20 °C: 157 kg
-circuit oil inventory at 300 °C: 113 kg
-maximum pressure allowable for the circuit: $p_{\max} = 15\, bar$
-minimum relative height of oil level: $\alpha = \frac{h_{\min}}{h_{press}} = 0.3$
-pressurizer diameter: D= 0.35 m

the total height of the pressurizer, due to expression (8) is 0.82 m resulting in a total volume of 79 litres.

4.4.4 Oil pump

The oil pump has to be identified according to available suppliers (a possible option could be a mag-drive centrifugal pump). A specific analysis of the suppliers and pump type has not yet been performed.

4.4.5 Measuring instrumentation

The main part of the instrumentation set will be pressure taps and Thermocoax™ brazed on SG tube walls (details will be given in the final report). One calibrated orifice for oil flow rate measurement or a coriolis flow meter will be adopted. Fluid bulk thermocouples at inlet and outlet heater collectors, at inlet and outlet SG bundle, at orifice inlet and at pressurizer inlet will be installed.
The instrumentation will be tested and validated at SIET (certified lab).

4.5 Circuit main data

Table 11

Oil loop-primary system main data

Oil heaters	
Number	6
Material	SS AISI 316
Tube schedule	40
Length [m]	5.3
Inner diameter [mm]	40.9
Outer diameter [mm]	48.26
Coil diameter [m]	0.5
Number of coils	3.4
Maximum current available [A]	3000 (250 A for each welder)
Maximum voltage drop [V]	150
Electrical connection with welders	Series of heaters with all welders in parallel
Pressure drops, @ overall flow rate 15 kg/s [kPa]	14.3
Electrical welders – Heating section	
Number	12
Maximum current per welder [A]	250
Maximum voltage drop [V]	150
Overall power available [kW]	450
Headers	
Material	SS AISI 316
Pipe schedule	40
Number	2
Length (for each header) [m]	1
Inner diameter [mm]	102.26
Outer diameter [mm]	114.3
Piping (heaters-to-SG, SG-to-heaters)	
Material	SS AISI 316
Overall length [m]	20
Tube schedule	40
Inner diameter [mm]	77.92
Outer diameter [mm]	88.9
Pressure drops @ 15 kg/s [kPa]	63.5

Steam Generator (SG) – Test section	
Material	SS AISI 316
Tube inner diameter [mm]	12.53
Tube outer diameter [mm]	17.11
Coil diameter [m]	0.6
Tube length [m]	32
Number of coils	17
Pitch/diameter ratio	2.5
SG height [m]	0.7
Gap [mm]	22
Throat [mm]	2.5
Gap inner diameter [mm]	589
Gap outer diameter [mm]	611
Pressure drops @ 15 kg/s [kPa]	56
Diathermic oil	
Type	SYLTHERM 800
Total loop inventory [kg]	170
Maximum allowable temperature [°C]	400
Estimated cost [€/liter]	15
Pressurizer	
Design pressure [bar]	15
Shape	Cylindrical
Diameter [m]	0.35
Height [m]	0.82
Volume [litres]	79
Gas	N_2
Minimum oil level from bottom [m]	0.25
Pump	
Type	Mag-drive centrifugal pump
Constructor	Finder Pompe (Merate) ?
Head[9][kPa, m]	134, 20
Max Flow rate [kg/s]	15
Power [kW]	4.4

[9] *Calculated on the basis of preliminary circuit design, the real value must be estimated on the basis of real circuit layout; in particular concentrated pressure losses due to bends and due to the calibrated orifice have not been included in the calculations.*

5 List Of Components

Position	Priority	Description	Features	Quantity	*Note*
basic facility			-	-	-
1	1	Main Globe Valves for Secondary Fluid (water/steam) Circuit	*Valvole a globo con tenuta a baderna, comando a volantino, corpo in acciaio al carbonio, connessioni flangiate, 3/4" + 1/2", DN 20, PN250, Temperatura esercizio 450°C, otturatore a pieno passaggio*	2	*Valvole di scarico* *BONETTI BLY, stellitate, anticavitazione*
2	1	Service Globe Valves for Secondary Fluid (water/steam) Circuit	*Valvole a globo con tenuta a baderna, comando a volantino, corpo in acciaio al carbonio, connessioni filettate (con possibilità di saldatura), ¼", PN250, temperatura esercizio 350°C (opzione 2: 450°C)*	4	*Valvole di sfiato/drenaggio/…*
3	1	Control Valve for Secondary Fluid (water/steam) Circuit	*Valvola a globo con otturatore profilato equipercentuale con tenuta sullo stelo a soffietto o baderna, comando pneumatico con elettroposizionatore, corpo in acciaio al carbonio, connessioni flangiate 3/4", DN 20, PN250, Temperatura esercizio 350°C, condizione max apertura: portata 0.8 kg/s, p in=250 bar, p out=210 bar, temperatura 350°C; min apertura: 0.04 kg/s, p in=20 bar, p out=10 bar, temperatura 212°C (efflusso bifase)*	1	*Valvola di laminazione, con attuatore motorizzato* *(A) BONETTI tipo BONT BLY, anticavitazione, con otturatore profilato (max portata=0.8 kg/s, minima dp= 40 bar)*
4	1	Control Valve for Secondary Fluid (water/steam) Circuit	*Valvola a globo con otturatore profilato equipercentuale con tenuta sullo stelo a soffietto o baderna, comando pneumatico con elettroposizionatore, corpo in acciaio al carbonio, connessioni flangiate 3/4" o 1", DN 20 o DN 25, PN250, Temperatura esercizio: 450°C, condizione max apertura: portata 0.8 kg/s,* ***[p in=10 bar, p out=2 bar, temperatura 180°C, fluido in: vapore saturo secco; min apertura: 0.04 kg/s, p in=250 bar, p out=2 bar, temperatura 270°C] DA VERIFICARE,*** *fluido in: vapore saturo secco supercritico*	1	*Valvola di scarico/controllo vapore, con attuatore motorizzato* *(B) BONETTI tipo BLB (max portata= 0.8 kg/s; minima dp= 30 bar; vapore surriscaldato)*

Position	Priority	Description	Features	Quantity	*Note*
5	1	Control Valve for Secondary Fluid (water/steam) Circuit	*Valvola a globo con otturatore profilato equipercentuale con tenuta sullo stelo a soffietto o baderna, comando pneumatico con elettroposizionatore, corpo in acciaio al carbonio, connessioni flangiate 3/4" o 1", DN 20 o DN 25, PN250, Temperatura esercizio: 450°C, condizione max apertura: portata 0.1 kg/s, p in=250 bar, p out=1 bar, temperatura 450°C, fluido in: vapore supercritico*	1	*Valvola di scarico/controllo vapore, con attuatore motorizzato* *(E) PARCOL ? Da valutare acquisto, in base a risposta della PARCOL su portate e regimi parziali*
6	1	Control Valve for Secondary Fluid (water/steam) Circuit	*Valvola a globo con otturatore profilato equipercentuale con tenuta sullo stelo a soffietto o baderna,* ***comando pneumatico*** *con elettroposizionatore, corpo in acciaio al carbonio, connessioni flangiate 3/4", DN 20, PN250, Temperatura esercizio 350°C (opzione 2: 450°C), condizione max apertura: portata 0.8 kg/s,* ***[p in=10 bar, p out=2 bar, temperatura 180°C, fluido in: liquido saturo; min apertura: 0.04 kg/s, p in=250 bar, p out=2 bar, temperatura 270°C, fluido in: liquido saturo] DA VERIFICARE***	1	*Valvola di scarico/controllo liquido, con attuatore motorizzato* *(C) BONETTI tipo BLB (max portata= 0.8 kg/s, minima dp= 30 bar)*
7	1	Control Valve for Secondary Fluid (water/steam) Circuit	*Valvola a globo con otturatore profilato equipercentuale con tenuta sullo stelo a soffietto o baderna, comando pneumatico con elettroposizionatore, corpo in acciaio al carbonio, connessioni flangiate 3/4", DN 20, PN250, Temperatura esercizio: 450°C, condizione max apertura: portata 0.1 kg/s,* ***[p in=10 bar, p out=2 bar, temperatura 180°C, fluido in: liquido saturo; min apertura: 0.04 kg/s, p in=250 bar, p out=2 bar, temperatura 270°C, fluido in: liquido saturo] DA VERIFICARE***	1	*Valvola di scarico/controllo liquido, pneumatica (per il controllo fine, in zona liquido)* *(D) max portata= 0.1 kg/s, dp= 250 bar*
8	1	Differential Pressure Transmitters	*p 200 kPa, pressione di corpo 250 bar, uscita 4-20 mA*	4	*Endress Hauser*
9	1	Differential Pressure Transmitters	*p 800 kPa, pressione di corpo 250 bar, uscita 4-20 mA*	4	*Endress Hauser*
10	1	Relative Pressure Transmitters	*range 0:250 bar, pressione di corpo 250 bar, uscita 4-20 mA*	2	*Endress Hauser*

Position	Priority	Description	Features	Quantity	Note
11	1	Flow Meter (water)	*Misuratore di portata ad effetto Coriolis (in grado di operare con acqua fredda max 100°C, alla pressione di 250 bar, portata min 0-0.01 kg/s, max 1.0 kg/s)*	1	*Endress Hauser*
12	1	DAS (Digital Aquisition System)	***Opzione 3***	1	*National Instruments Ing.Colosio - TEORESI*
13	1	Thermocouples	*TC K ANSI SPECIAL, D=3mm; L=250mm*	5	*ITALCOPPIE*
14	1	device for TC	*termolock*	5	
15	1	device for TC	*connettori ANSI per TC*	5	
16	1	Wattmeter	*Wattmetro*	1	
17	1	DAS (Digital Aquisition System) - PLC	*CJMCPU12 PLC - CPU* *CJ1WPA202 PLC - power* *CJ1WID211 PLC - Dig.in* *CJ1WOD212 PLC - Dig.out* *CS1W-CN226 PLC - cavo*	1 1 1 1 1	*Cavallanti - OMRON*
18	1	DAS (Digital Aquisition System) – Signal Generation/Conversion from Instrumentation	*EUROHM, Resistore E20032-250, Resistore 250ohm* *IFE – PC, Telemecanique AB1D11435U, Morsetto 4P* *SELFOR –PC, QUINT PS, Alimentatore 24Vdc* *PRELECTRONICS, PR4116, TC converter* *PRELECTRONICS, PR4501, programmer* *WEIDMULLER, 8560740000, Convertitore/isolatore*	16 16 1 5 1 4	
19	1	DAS (Digital Aquisition System)	*Personal Computer per gestione controlli – acquisizione ed elaborazione dati*	1	
20	1	Instrumentation	*Convertitore di segnale ad alto isolamento elettrico, per corrente di shunt (Gandolfi)*	1	
21	1	Instrumentation	*Convertitore di segnale ad alto isolamento elettrico, per misurare tensione sulla sezione di prova (Gandolfi)*	1	
22	2	Heated Thermocouples			
23	2	Electric Pre-Heater for Secondary Fluid (water)	*Monotubolare 1/2" con flange isolanti ed alimentazione elettrica diretta, struttura di supporto e protezione, termocoppie di sicurezza, potenza max 1000 kW*	1	

Position	Priority	Description	Features	Quantity	*Note*
24	2	Test section (helical coil tube) - direct heating	*Monotubolare (dimensioni da definire secondo matrice di prove), con flange isolanti ed alimentazione elettrica diretta, struttura di supporto e protezione, termocoppie di parete, potenza max 450 kW*	N	*Parametri da definire (numero di test section, diametri tubi, lunghezze, spessori)*

advanced facility (oil system)

21		Low Pressure Recirculation Pump for Primary Fluid (Oil) Circuit	*Portata 20 l/s, prevalenza 10 m, Pompa centrifuga con tenute raffreddate in grado di veicolare olio diatermico a 320 °C*	1	
22		Charging/ Discharging Pump (oil)	*Portata 2 l/s prevalenza 20 m, Pompa a palette od ingranaggi a funzionamento reversibile, Max temperatura di funzionamento 150-200 °C*	1	
23		Main Globe Valves for Primary Fluid (Oil) Circuit	*Valvole a globo con tenuta sullo stelo a soffietto, comando a volantino, corpo in acciaio al carbonio, connessioni flangiate 4" ANSI300 o DN 100PN16*	2	
24		Service Globe Valves for Primary Fluid (Oil) Circuit	*Valvole a globo con tenuta sullo stelo a soffietto, comando a volantino, corpo in acciaio al carbonio, connessioni flangiate 1"1/2" ANSI300 o DN 40 PN16*	4	
25		Control Valve for Primary Fluid (Oil) Circuit	*Valvole a globo con otturatore profilato equipercentuale con tenuta sullo stelo a soffietto, comando pneumatico con elettroposizionatore, corpo in acciaio al carbonio, connessioni flangiate 4" ANSI300 o DN 100PN16*	1	*kv da determinare successivamente*
26		Primary Fluid (Oil) Heater	*La potenza sarà circa 450 kW*	1	*Occorre definire se utilizzare riscaldamento diretto od indiretto (che potrà essere utile nel caso di fluidi conduttori, es. piombo)*

Position	**Priority**	**Description**	**Features**	**Quantity**	***Note***
27		Primary Fluid (Oil) Tank for Test Section	*Contenitore d'olio diatermico, a pressione atmosferica o a ba ssa pressione (<10 bar), in grado di distribuire olio ad una sezione tubolare elicoidale. A livello preliminare si può pensare ad un contenitore cilindrico di 2 m di altezza ed 1 m di diametro, in SS-AISI 316 L, con tubi di collegamento ed internals.*	1	*Eventuale compatibilità con uso Piombo da valutare.*
28		Primary Fluid (Oil) Reservoir	*Contenitore d'olio diatermico per il carico/scarico nel circuito della sezione di prova.*	1	
29		Diathermic Oil	*Olio diatermico per la simulazione del fluido riscaldante primario (resistenza a temperatura 330°C)*	5 m^3	*Selezione dell'olio da effettuare in base a proprietà fisiche*
30		Test section (helical coil tube/bundle) - indirect heating	*Monotubolare (dimensioni da definire secondo matrice di prove), con flange e struttura di supporto del fascio di tubi, struttura di protezione, termocoppie di parete, potenza max 450 kW*	N	*Parametri da definire (numero di test section, diametri tubi, lunghezze, spessori)*
31	1	Flow Meter (oil)	*Misuratore di portata ad effetto Coriolis (in grado di operare con olio max 350°C, alla pressione di 10 bar, portata min e max da valutare)*	1	*Endress Hauser*

O&M activities on SIET plants

32	1	High Pressure Volumetric Pump for Secondary Fluid (water)	*Pompe Gallaratesi - Portata 0.4 l/s, prevalenza 2000 m, Pompa volumetrica con corsa modulabile con continuità; Manutenzione straordinaria delle tenute delle pompe gallaratesi (attualmente hanno una guarnizione che non scorre ad alta pressione)*	1	*COMPONENTE SIET, non da acquistare (costo di ripristino)*
33	1	Electric Power Supply Section for Test Section heating (Welding Machines) and pumps	*n° 12 Saldatrici in CC, potenza 37.5 kW cad., Voltaggio=150 V, max CC=250 A; ristrutturazione parte elettrica di potenza per pompe Gallaratesi e saldatrici*	-	*COMPONENTE SIET, non da acquistare (costo di ripristino)*
34		Sbarre in rame	*Sbarre in rame per connettere le saldatrici alla sezione di prova*	1	

Position	Priority	Description	Features	Quantity	*Note*
others					
		TIG welding machine	*Saldatrice per realizzazione di termocoppie*	1	*Da valutare con SIET la opportunità dell’acquisto*
		Bending System	*Macchina per la creazione di tubi elicoidali (piegatura continua)*	1	*Da valutare opportunità dell’acquisto.*

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