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# THE FIRST LINX-2 TESTS

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*An experimental programme was performed in the LINX-2 facility to assess the performance of the thermal hydraulic design of a proposed containment condenser. This component is part of a double, concrete containment proposed by ENEL (the Italian Electricity Company) as a European alternative to the Westinghouse AP600 single-shell metallic containment. The LINX-2 test section corresponds to the preliminary design of one of the sixteen condenser units, and has a heat transfer surface scaled 1:25. It is a compact finned-tube heat exchanger with steam condensation outside the tubes and water evaporation inside. The LINX-2 tests were performed under controlled forced-flow conditions covering the range expected in the containment. The effects of pressure, flowrate, non condensable fraction, and coolant temperature on heat transfer performance were investigated. These tests complemented natural circulation experiments performed by ENEL, and the data were used to optimise the condenser design.*

## 1 GENERAL FRAMEWORK: LINX PROJECT

Advanced Light Water Reactors (ALWR) under design in various countries will typically include Passive Containment Cooling Systems (PCCS). The LINX (large-scale investigation of natural circulation, condensation and mixing processes) project dealt with mixing and condensation processes involved in these systems. More specifically, issues relevant to the General Electric Simplified Boiling Water Reactor (SBWR) and a European version of the Westinghouse Advanced Pressurised Water Reactor (AP-600) concepts were addressed [1]. The results of these studies are, however, of general interest for all passive containment cooling concepts. Among other analytical and experimental activities, the LINX project included the construction of the LINX-2 facility and a series of AP-600 related tests. This test campaign, which constitutes the subject of this paper, was launched in 1994 as a joint activity with ENEL (the Italian Electricity Company) and involved a PCCS proposed for the European version of the Westinghouse AP-600 [2]. The tests have been performed in 1996.

## 2 ENEL INNOVATIVE CONTAINMENT COOLING

### 2.1 Passive Containment Cooling System (PCCS)

The European Utility Requirements for future reactors (EUR), which are under development, ask for a rugged containment, able to mitigate external hazards (airplane crash and pressure wave) and hypothetical severe accidents involving core melt. One of the preferred containment configurations for European future plants is the double concrete containment. The ENEL project consists of a double-envelope concrete containment for the European version of the AP-600 rather than the original metallic envelope containment. In the event of a Loss of Coolant Accident (LOCA), when steam escaping from the reactor pressure vessel heats and pressurizes the containment atmosphere, a concrete containment would not be able, as a metallic one is able, to conduct heat to the environment to reduce the containment pressure. Thus the proposed PCCS for the European AP-600 employs condensers deployed within the containment to condense steam generated during the LOCA and to reduce the pressure. The heat is transmitted to the environment through an intermediate loop which penetrates into the containment (Fig. 1). The condenser consists of a bundle of 112 finned tubes oriented at 25° incline, and is surrounded by a duct to promote a natural circulation draft of air and steam through the condenser tubes. The heat of condensation is transferred to a steam-water mixture flowing through the tubes in a closed, natural circulation thermosiphon loop. This intermediate loop passes through the concrete walls, and is cooled by a second heat exchanger located on top of the containment building. Heat exchange to the environment takes place in a hybrid cooling tower that combines a water pool and natural draft cooling tower.

The use of finned tubes in a condensing heat exchanger is not common. It allows reduction in condenser size, but raises some physical problems such as the non-condensable gas / condensate distributions between / along the fins. Accumulation of non-condensables and condensate along the fins might degrade condenser performance.

### 2.2 Internal heat exchanger tests at PSI

The heat removal capacity of the condenser depends both on the natural circulation conditions in the containment and on the efficiency of the condenser itself. Unfortunately, it is not possible to separate these two effects in natural circulation experiments. In particular, the gas velocity through the condenser tube bundle cannot be independently controlled. Therefore, in addition to tests performed by ENEL with natural circulation, a reduced-scale condenser was tested in the LINX-2 facility under controlled forced-flow conditions. The investigation included the effects of pressure, flow rate, non-condensable fraction and coolant temperature on heat transfer efficiency. The results of these tests are used to optimise the finned condenser design and to improve computational models of condensation heat transfer in similar geometries.

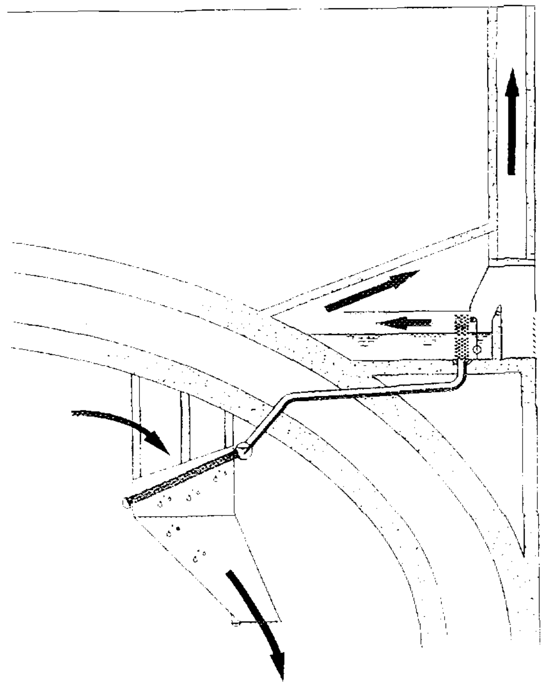

**Fig. 1:** The Passive Containment Cooling System (PCCS) proposed by ENEL for a European version of the Westinghouse AP600, with a double concrete containment.

## 3 THE LINX-2 FACILITY

### 3.1 Basic capabilities

The LINX-2 facility is a multipurpose, medium-scale experimental setup used for a variety of experiments. The facility consists of a large pressure vessel (3.5 m high, 2 m diameter) rated at 10 bars and 250°C. Regulated steam injection into the vessel can be provided over the range of 10-120 kg/h, and for air injection between 0.1 and 75 kg/h. External heating and cooling systems are available for system conditioning, and these have heating and cooling powers of 140 and 120 kW, respectively.

### 3.2 Configuration for internal condenser tests

Construction and instrumentation of the LINX-2 facility were completed in 1994. In 1995, the LINX-2 facility (which was then ready for the SBWR-related experiments) was modified for the passive European PWR-related tests and the SBWR experiments were postponed. During this time a gas recirculation loop was added to generate forced recirculation through the test condenser. An external, natural circulation two-phase loop for cooling the condenser was also constructed, thus simulating the intermediate loop. The modified LINX-2 set-up was commissioned in 1995 and the PWR PCCS-related experiments were performed in 1996.

A scheme of the modified LINX-2 facility is given in Fig. 2. The test condenser is enclosed in the LINX-2 pressure vessel. During the tests, a steam/air mixture is injected at the top of the vessel and forced to flow downwards through the condenser. A horizontal screen placed between the condenser's outer casing and the vessel wall prevents the steam/air mixture from by-passing the condenser. A deflection plate below the flow inlet at the top of the pressure vessel helps to produce a uniform flow at the condenser inlet. As the gas mixture passes through the condenser, part of the steam condenses, remaining as condensate at the bottom of the vessel. The remaining portion of the steam/air mixture is recirculated by the external fan. Droplets carried with the steam are de-entrained by a separator at the vessel outlet. A "make-up" steam flow from a steam generator replaces the condensed steam, and is introduced near the bottom of the recirculation loop. The steam injection and gas recirculation piping is electrically heated to prevent condensation. The test condenser tubes are internally cooled by boiling water and are connected to a natural-circulation two-phase loop that discharges the two-phase mixture into a small vessel, which is positioned about two meters above the main vessel. Steam entering the small vessel is condensed by an auxiliary heat exchanger and the condensate returns to the test condenser. The external secondary condenser is cooled by water supplied by the LINX-2 external cooling system.

During the internal condenser tests, the "make-up" steam and recirculated gas flow rates are measured (F7 and F11 in Fig. 2). In the main vessel, the pressure near the top is measured (PA1), as well as the gas temperature at the vessel inlet (T35), at the test condenser inlet (T37) and at several locations near the test condenser outlet (T24-T33). In the two-phase cooling loop connecting the secondary heat exchanger to the test condenser, the absolute pressure is measured close to the main vessel inlet (PA5). The condenser tube inside coolant temperature is obtained from this pressure measurement assuming saturation. The mass flow rate and temperature in the external cooling loop are measured (F8, T9) and kept constant. The temperatures at the secondary heat exchanger coolant inlet and outlet (T22, T23) are measured, allowing calculation of heat removal from this heat exchanger. In addition to the required instrumentation, a humidity measurement in the recirculation loop using a customised oxygen probe was developed and used during the tests. This redundant measurement confirmed the accuracy of the flow rate measurements and mass balances performed.

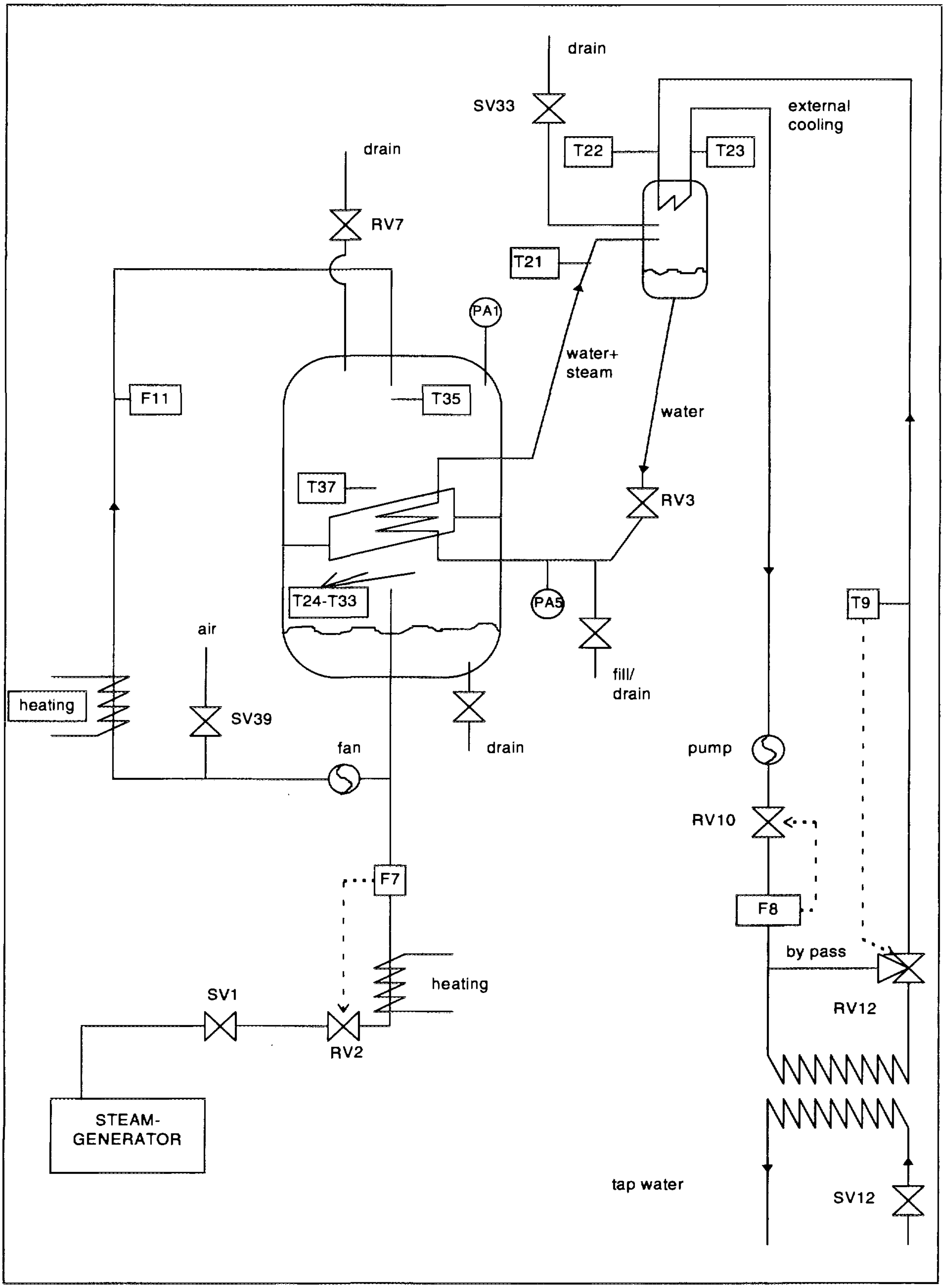


**Fig. 2:** LINX-2 configuration for ENEL internal heat exchanger tests.

T, PA and F indicate temperature, absolute pressure and flow rate measurements; SV and RV are shut-off and regulating valves.

## 4 INTERNAL HEAT EXCHANGER CHARACTERISATION TESTS

### 4.1 Test specification

The test section was a mockup of a preliminary version of the finned-tube condenser designed by ANSALDO. Sixteen units are envisioned for the containment of the European version of the AP-600.

The scaling factor, based on the heat transfer surface, was $1/25^{th}$ of a single full-sized unit. Each of the forty tubes in the test condenser was 860 mm long. The characteristic parameters commonly used in heat exchange and fluid flow correlations, i.e. packing thickness, minimum flow area in the packing and hydraulic diameter were conserved.

The reference values for the condenser characterisation test matrix were obtained by scaling down the PCCS preliminary design conditions specified by ENEL. The reference cooling power, 30 kW, represents 1/25 times $1/15^{th}$ of the reactor decay heat 24 h after a LOCA (fifteen among the sixteen available condenser units are assumed to be operational). The nominal tube-side coolant temperature is 100°C, corresponding to boiling conditions in the external cooling pool. The air partial density in the steam/air mixture circulated through the test condenser corresponds to the initial air content in the containment at atmospheric pressure.

### 4.2 Test matrix

The dependence of heat removal capacity on coolant temperature, air partial density and gas velocity was investigated over a wide range around the reference values. The cooling power was varied from 15 to 60 kW and the coolant temperature from 50 to 120°C. Varying the air partial density is also of interest because inhomogeneous temperature distributions within the containment can produce local increases in the air content, degrading condensation heat transfer. Tests included air partial densities up to 150 % of the nominal value. The effect of the mass flux in the condenser was also investigated. The flow range of 0.1 to 0.5 kg/s for these tests covers the velocities expected in real operation under natural convection conditions within the containment. Finally, the influence of steam superheating, which may occur locally in the containment under severe accident conditions, was investigated for superheats ranging from 0 to 25°C. Thirty-four steady-state tests were performed with various combinations of the control variables.

### 4.3 Test procedure

The objective of the test procedure is to establish a steady state at the required test conditions, i.e., make-up steam and recirculated gas flow rates, coolant temperature and air partial density. The make-up steam flow rate is first set and then the condenser tube inside coolant temperature is adjusted through the external coolant flow rate and temperature. The recirculated gas flow rate is adjusted through the fan rotation speed and the proper air partial density is established by injecting air or purging a portion of the steam/air mixture from the system. In practice, only the make-up flow rate can be independently established while all other parameters are interdependent.

Test facility operation was delicate due to strong interactions between the three loops involved and control difficulties inherent to natural circulation loops. Adjustment of the test parameters to obtain steady-state conditions required up to fourteen hours. However, for all "validated" tests, the test specifications were fully met: the values of the test parameters were very close to the planned test matrix values and completely steady states could be reached.

### 4.4 Results

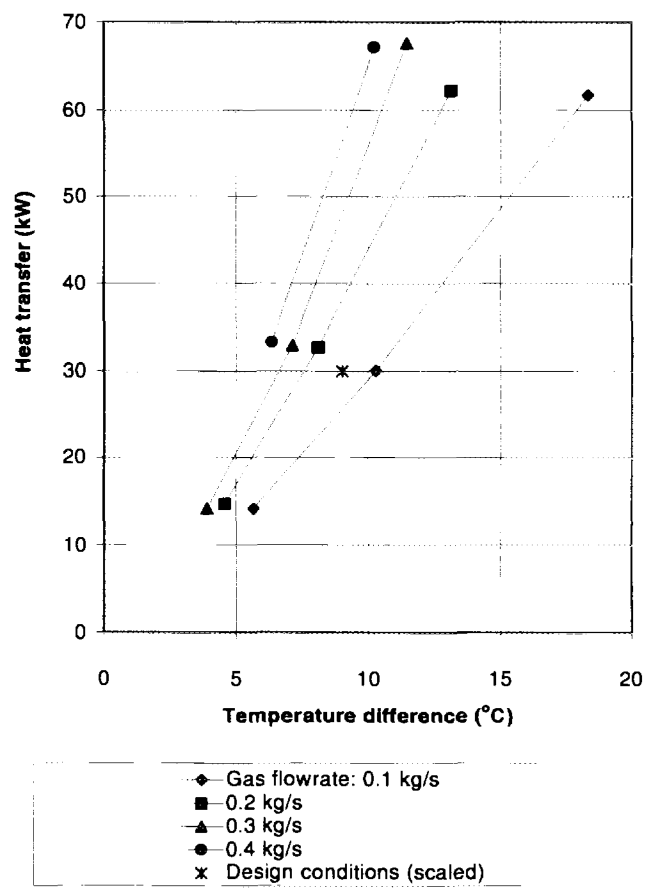


**Fig. 3:** Effect of gas flow rate on heat exchanger performance at constant air partial density (1 $kg/m^3$) and coolant temperature (100°C).

The critical issue in assessing condenser performance is determination of the energy transferred from the flowing steam/air mixture in the main vessel to the condenser. This is accomplished with two independent energy balances: the first is performed in the main vessel and the second on the coolant used in the secondary heat exchanger. An error analysis based on the measurement uncertainties showed that the second energy balance is more accurate than the first, and therefore the secondary heat exchanger energy balance is used to assess condenser performance while the energy balance in the main vessel is used as a cross check.

The influence of the various relevant parameters on heat transfer performance was investigated and a sample of the results is presented in Figs. 3-5. The results are displayed as graphs of heat transfer rate in the test condenser vs. difference between the steam/air mixture inlet temperature and the two-phase coolant temperature for various values of the other control parameters.

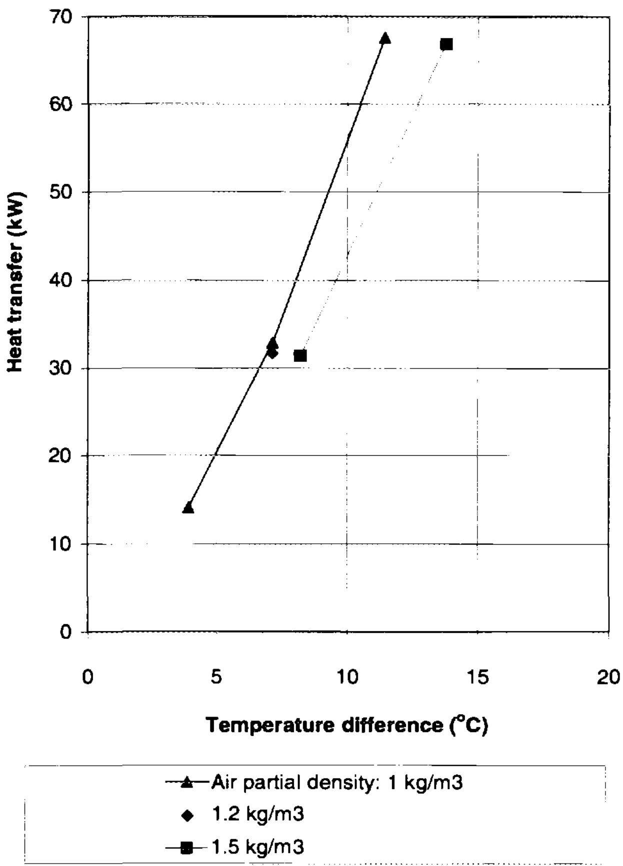


**Fig. 4:** Effect of air partial density on heat exchanger performance at constant gas flow rate (0.3 kg/s) and coolant temperature (100°C).

The systematic investigation of the effect of the inlet flow rate in the forced-flow LINX-2 tests has shown that it has a significant influence on condenser performance. This is shown in Fig. 3, where the test condenser operating points are shown for various gas flow rates, together with the operating point corresponding to the design conditions 24 h after a LOCA. The expected natural circulation gas flow rate at the inlet of the full-scale condenser (scaled for direct comparison with the LINX-2 data) is about 0.3 kg/s. At this flow rate the test condenser has about 60% excess heat removal capacity over the design value (Fig. 3). However, for very low gas flow rates, about 0.1 kg/s and lower, condenser performance would drop below design specifications. Previous small-scale natural circulation experiments by ENEL indicated that the design flow rate assumption is conservative [3], and large-scale natural circulation tests are being performed at the Westinghouse Large Scale Containment Test Facility (LSCTF) to verify whether the results from small scale tests are applicable to more representative geometries.

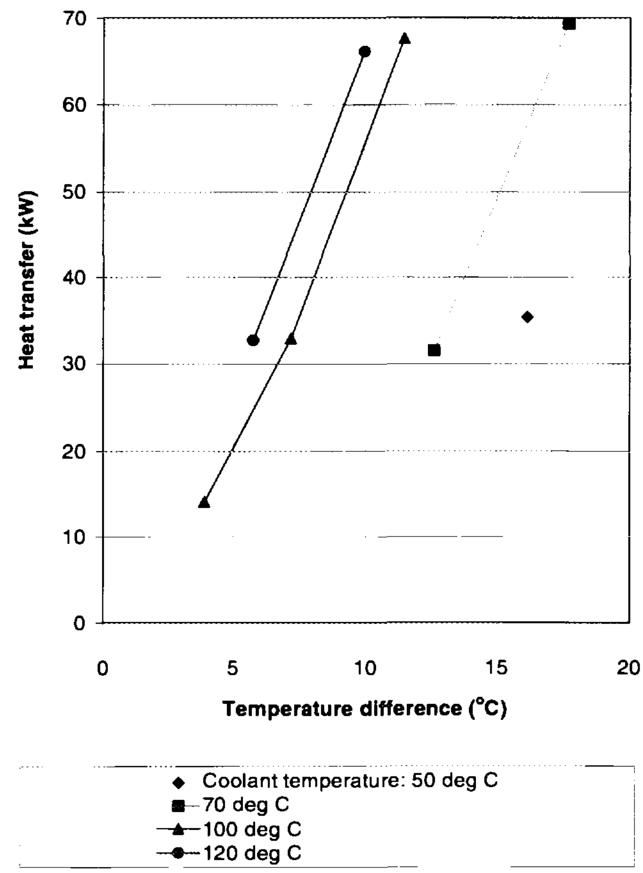


**Fig. 5:** Effect of coolant temperature on heat exchanger performance at constant gas flow rate (0.3 kg/s) and air partial density (1 kg/m³).

The air partial pressure at the test condenser inlet had little influence within the range investigated (Fig. 4), but the heat removal capacity at a given steam-coolant temperature difference increases strongly with coolant temperature (Fig. 5). This is due to the rapid increase in steam saturation pressure with the temperature. The steam mass flux from the gas bulk to the condensation interface is much higher at high steam partial pressure.

Based on the large performance margin provided by the preliminary condenser design (Fig. 3 and comments), ANSALDO re-designed this component, with reduced tube length and number. The LINX-2 results are presently being analysed in more detail. The purpose of the analysis is to assess, improve and complement the available models and correlations for the heat and mass transfer between the steam/air mixture and the finned tubes.

## 5 CONCLUSION AND ONGOING WORK

The first LINX-2 tests have shown that the solution retained by ENEL for the containment condenser, i.e., a compact, finned tube heat exchanger, is adequate. Based on the results, the condenser design was optimised. The results are also being used to assess and develop heat and mass transfer models for this component.

A continuation of the LINX project is now underway. Thanks to the acquired experience and LINX-2 facility availability, it was possible to include some contributions in two proposals to the Nuclear Fission Program of the 4$^{th}$ Framework Research and Technological Development Program of the European Union (EU) in cooperation with numerous European partners. Both are being funded and assure continuation of the major research directions for the LINX project for another three years.

The LINX-2 contributions to the EU projects are related to the European version of the passive AP-600 mentioned here (INCON project), and to a project on an advanced European Boiling Water Reactor (TEPSS project).

## 6 ACKNOWLEDGEMENTS

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