EXPERIMENTAL APPROACH FOR THE INVESTIGATION OF LNG SPILLS ON WATER SURFACE

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An experimental facility has been designed for small scale cryogenic pool spreading experiments on water surface. The experimental set up allows registering the temperature trends along water depth during cryogenic boiling, thus supporting the investigation of heat transfer between water surface and cryogenic layer, which rules the pool spreading and the consequent evaporation. The preliminary results obtained with the experimental facility will be presented and discussed.

1. INTRODUCTION

In international natural gas market, Liquefied Natural Gas (LNG) is getting more and more important, as ship transport development made liquefaction and regasification processes competitive with traditional pipeline transport. According to the analysis of past accidents which involved LNG (Sabatini 2010), it was evidenced that the major part of the records referred to transportation of LNG rather than storage or process phases. Therefore, specific scenarios expected during LNG transportation should be taken into account in order to define a comprehensive risk profile of this particular technology. Besides, the development of off-shore terminal for regasification and the increasing trend in LNG ship transportation, give rise to the definition of specific scenarios following the LNG spill on water surfaces.

Following a LNG spill, some vapour is immediately generated but, since LNG is stored as a saturated liquid at relatively low pressures, typically ranging between 1 and 4 bar (Cusiter et al. 2006, Gulati 2004, Tusiani and Shearer 2007), only a small part flashes, e.g. immediately evaporates after the release and the rest of the liquid forms a pool. The vapour generated by the pool is the major contribution to the cloud formation. Therefore, modelling LNG pool spreading and vaporization is a crucial step for the evaluation of damage distances in case of fire dispersion (e.g. the effect of flash fires, or the input for a vapour cloud explosion study).

From a literature review on experimental activity in this framework (Luketa-Hanlin 2006, Boyle and Kneebone 1973, Burgess et al. 1970), a lack of experiments on small and pilot scale is evidenced. Moreover, a specific focus on LNG spill on water surfaces is still missing.

Therefore, in order to support the future model development and validation, thus providing crucial data for managing risk connected with LNG facilities, an experimental device has been designed for small scale cryogenic pool spreading experiments.

The major key-points of the present activity are the followings:

- Investigate about heat transfer from water to cryogenic and heat dispersion into water;
- Experimental conditions which reproduce still water conditions;
- Geometry should not influence the data obtained (pool spreading was of not primary interest in this work, thus one-dimensional profiles are reported).

The results obtained with the experimental facility will be reported and discussed in the following sections.

2. MATERIALS AND METHODS

2.1 Description of the experimental set up

An overview of the experimental facility, located in the laboratories of the Chemical Engineering Department at University of Pisa, is shown in Figure 1, while Figure 2 reports the sketch with the corresponding dimensions (in mm).

The pool container is made of Plexiglas, 3 mm thick, in order to obtain a certain degree of visibility of cryogenic and water body during the experimental runs.

The pool dimensions were suitable for the amount of cryogenic released during runs: as nitrogen is usually contained in 10 L dewars, bigger water surfaces were not necessary to avoid boundary effects in spreading. The ten “windows” that can be seen along pool length are the positions of measuring devices (i.e., thermocouples, as described later). They have been designed in order to be substituted, if different measuring position would be necessary, and have rubber seals to avoid water leakages. A slipping surface was designed to minimize turbulence during cryogenic release (due to the impact of cryogenic liquid with water surface, see Figure 1), having the chance to go up and down in order to be partially submerged in the water. This surface has been realized in aluminum, which was considered more suitable to be in direct contact with the very low temperatures of cryogenic.

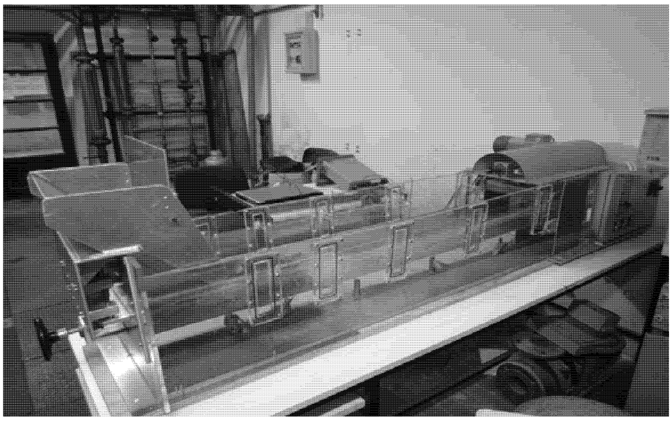

Fig. 1: Experimental device overview.

As stated in Section 1, the aim of the experimental run was to investigate heat transfer mechanism between water and cryogenic: in particular, to investigate about convection contribute in heat transfer.

To achieve this scope, water temperature trends along the depth have to be obtained, so the pool was equipped with a set of thermocouples (type K, Ni/Cr, with an accuracy of ± 0.5°C) placed at various depths, as shown in Figure 3.

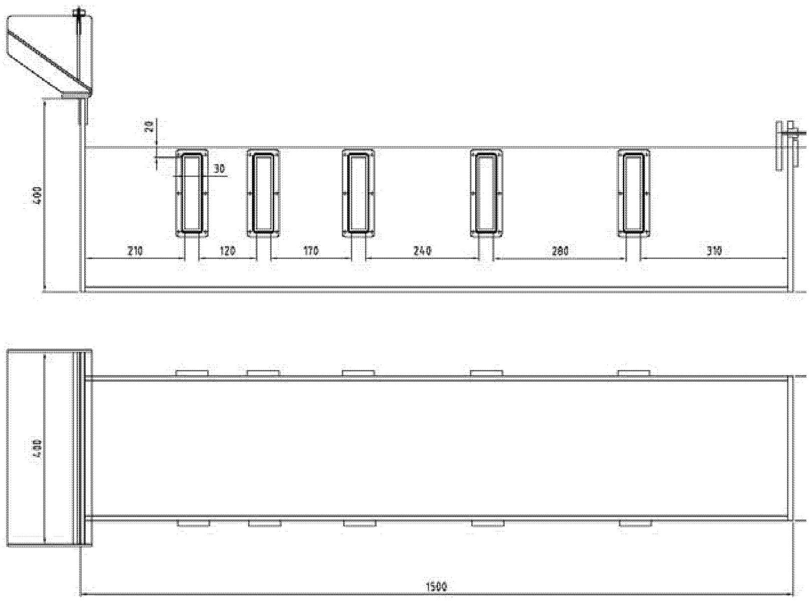

Fig. 2: Experimental device sketch (dimensions are expressed in mm).

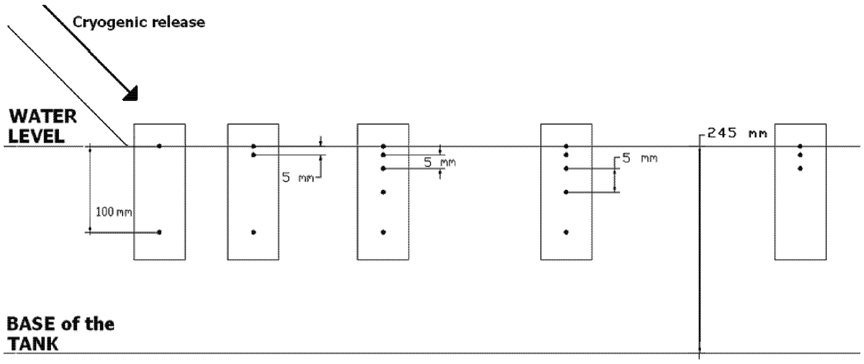

Fig. 3: Thermocouples position.

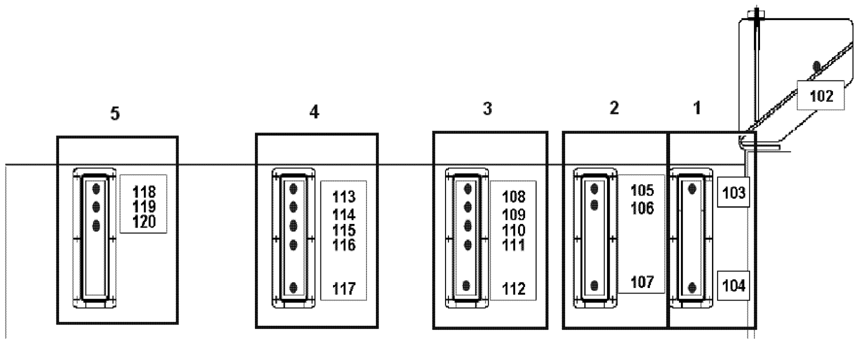

Fig. 4: Thermocouples and windows tags.

In addition, a thermocouple was positioned on the slipping surface. For acquisition convenience, thermocouples have been numbered, as well as windows, following scheme in Figure 4. These reference numbers will be used in the whole data and results discussion.

Data from thermocouples have been acquired using a commercial data logger (Agilent ® 34970A), suitable for multiple inputs acquisition.

2.2 Test procedure

An experimental procedure has been schematized, in order to assure the reproducibility of each run. The step procedure is reported below:

- Acquisition system is connected to the thermocouples and is set for experimental run
- Aluminium surface is cooled using a small amount of cryogenic nitrogen (namely LN2) (#102 temperature should be about 9-10°C)
- Acquisition system is stopped and started up again
- LN2 dewar is weighted
- LN2 release starts. Release duration (variable following our objective) is measured
- Ice thickness is evaluated by visual observation through transparent wall.
- Ice layer surface is estimated using thermocouples position, and its discontinuity is observed.
- Evaporation time is measured during experimental trial.
- LN2 dewar is weighted again to evaluate LN2 amount

Temperature measurement lasts until the whole system is stationary (ice layer is completely melted and water temperature are more or less back to initial values)

As already said, release rate was not measured, but only total amount of LN2 released was measured, as well as release duration, so an average release rate can be evaluated. Nevertheless, release rate is not a relevant parameter for heat transfer modelling.

Ice thickness was not measured, but its value was estimated (with an accuracy of about ± 1 mm) and the estimate thickness will be compared with value from the model simulation.

Evaporation time is measured during the experimental run, and can also be derived from temperature trends of surface thermocouples.

3. PRELIMINARY RESULTS

3.1 Presentation of a sample run

A sample run is discussed hereby, in order to describe the type of results obtained in the current experiment. The main features needed to identify the experiment are reported in Table 1.

Table 1: Sample run features

LN2 Amount	Release duration	Ambient temperature
1.9 kg	30 s	17.8°C

TC 102 measurements

Temperature trends of TC 102 are reported in Figure 5. The grey dots represent release phase, which can be easily identified using this thermocouple.

Window n.1

Temperature trends of TC 103 and 104 are reported in Figure 6. As it’s clear from the temperature values, there’s no ice formation in this window, which is sited at the release point. The reason is the local turbulence, due to the impact of LN2 on the water surface, and the high momentum of the liquid flowing away on the water.

Window n.2

Temperature trends of TC 105, 106 and 107 are reported in Figure 7. In this window too, as in window 1, there's usually no formation of ice layer, essentially for the same reasons. Sometimes, especially for longer releases, a thin layer forms, but thickness is extremely small, and it's not a continuous surface, so it melts in a very short time.

Window n.3

This window, together with the following n.4, is the most significant, as boundary effects are not relevant as for n. 1, 2 and 5. These two sets will be taken into account in the modelling phase.

Figures 8, 9 show temperature trends for window n.3 thermocouples. There is always ice formation (as shown by the temperature trends of TC 108), and ice under cooling (due to sensible heat flow from ice to boiling LN2) is also evident. From temperature trends it's possible to estimate time of complete evaporation of LN2 film (evaporation lasts until the temperature keeps decreasing). Lower thermocouples (109-110-111) experience smaller temperature decrements (about 3-4 degrees maximum) and temperature trends report ripples, suggesting an eventual convective contribute, due to the high temperature difference between ice layer and water body. TC 112, the lowest, shows the smallest temperature decrement(about 1°C) and negligible ripples.

Window n.4

Thermocouples of window n.4 show the same trends as n.3 ones, as it's reported in Figures 10,11.

Window n.5

Window n.5 is the last one, the farthest from the release point, and it's situated under the metallic net protecting moving device. It's much influenced by boundary effects, as LN2 film accumulates at pool final wall, and vapour dispersion is depressed by the net. All these factors result in a thicker ice layer, and longer evaporation times, as shown in Figures 12 and 13.

In all the following Figures, T (temperatures) are expressed in °C and t (time) in seconds.

3.2 Discussion of the preliminary results

General considerations can be made from experimental runs, and may represent inspiration for further experimental or modelling activities:

- In still water runs, ice always forms (even with different surfaces and thickness) and in a very short time (2-3 seconds, very small times with respect to release and evaporation time)
- As expected, ice doesn't form near release point, due to local turbulence and LN2 momentum. Ice doesn't form even in presence of metal obstacles due to the structure of the tank itself.
- It was not possible to measure ice thickness, but from the observation during runs it was estimated to be in a range of 3-7 mm for still water runs (depending on LN2 quantity and release duration).
- Surface temperature is much higher than the expected one, i.e. LN2 boiling temperature (77K). Further investigation may be useful in order to understand this (vapour film overheating may happen)

Under water surface, temperature trends have "ripples" suggesting that convection happens, due to big ΔT between cryogenic and water. Ripples don't seem to be connected to ice presence, as they happens even in areas where ice doesn't form. Modelling activity may help to evaluate the different contributions of conductive and convective heat transfer.

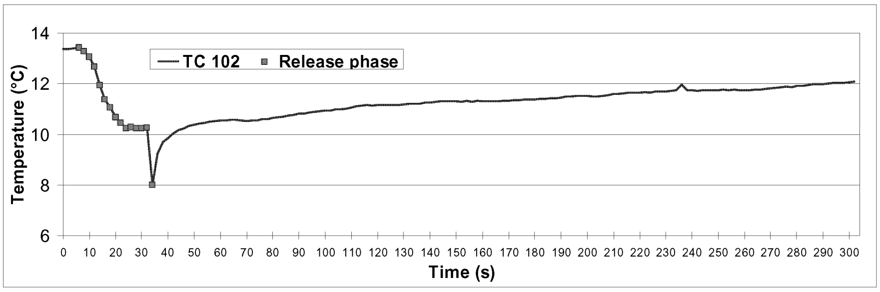

Fig. 5: TC 102 trend. Time is reported in s, temperature is reported in °C.

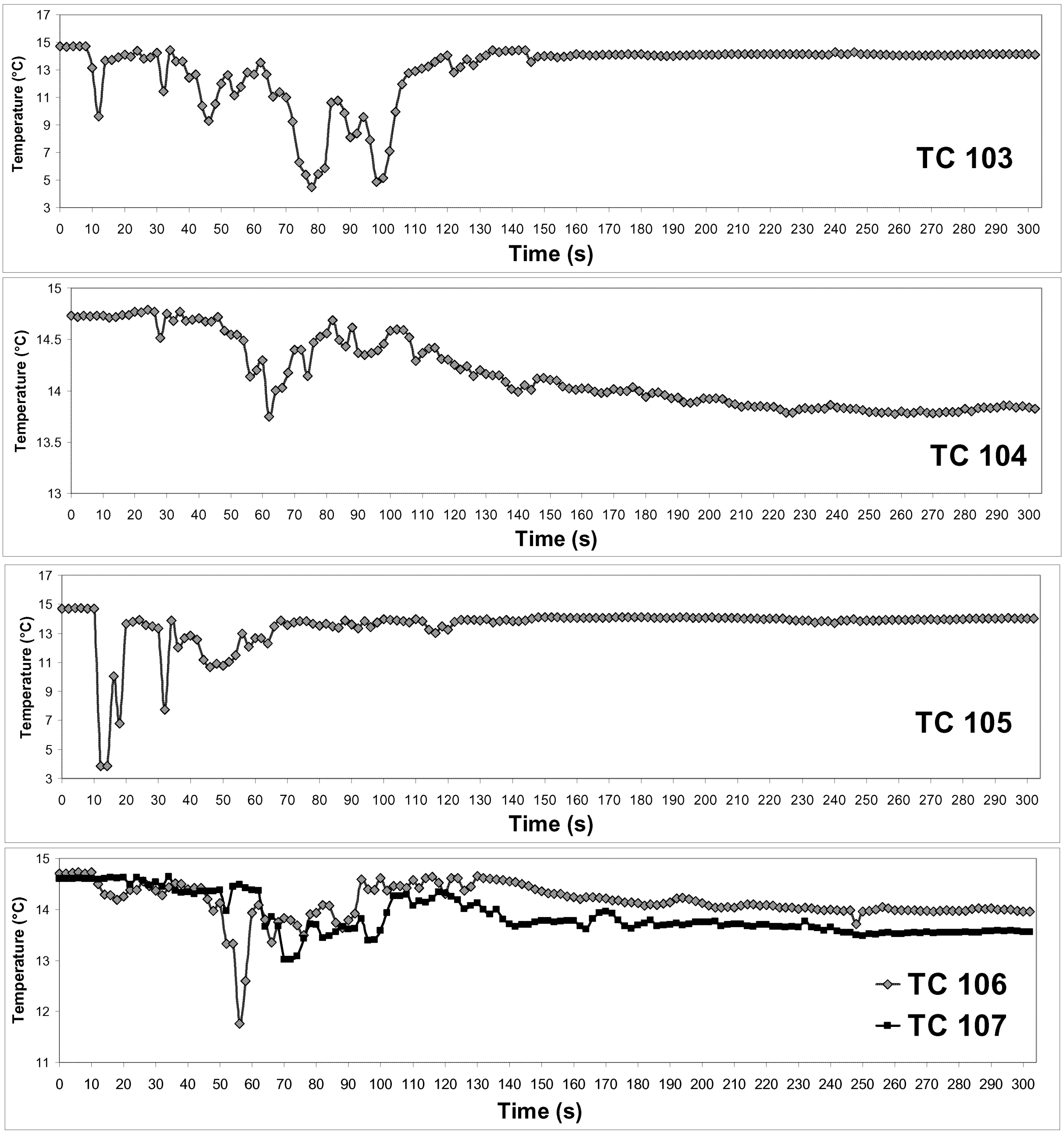

Fig. 6:. Temperature trends for TC 103, 104 (window 1) and TC 105, 106, 107 (window 2). Temperature is in °C, time in s.

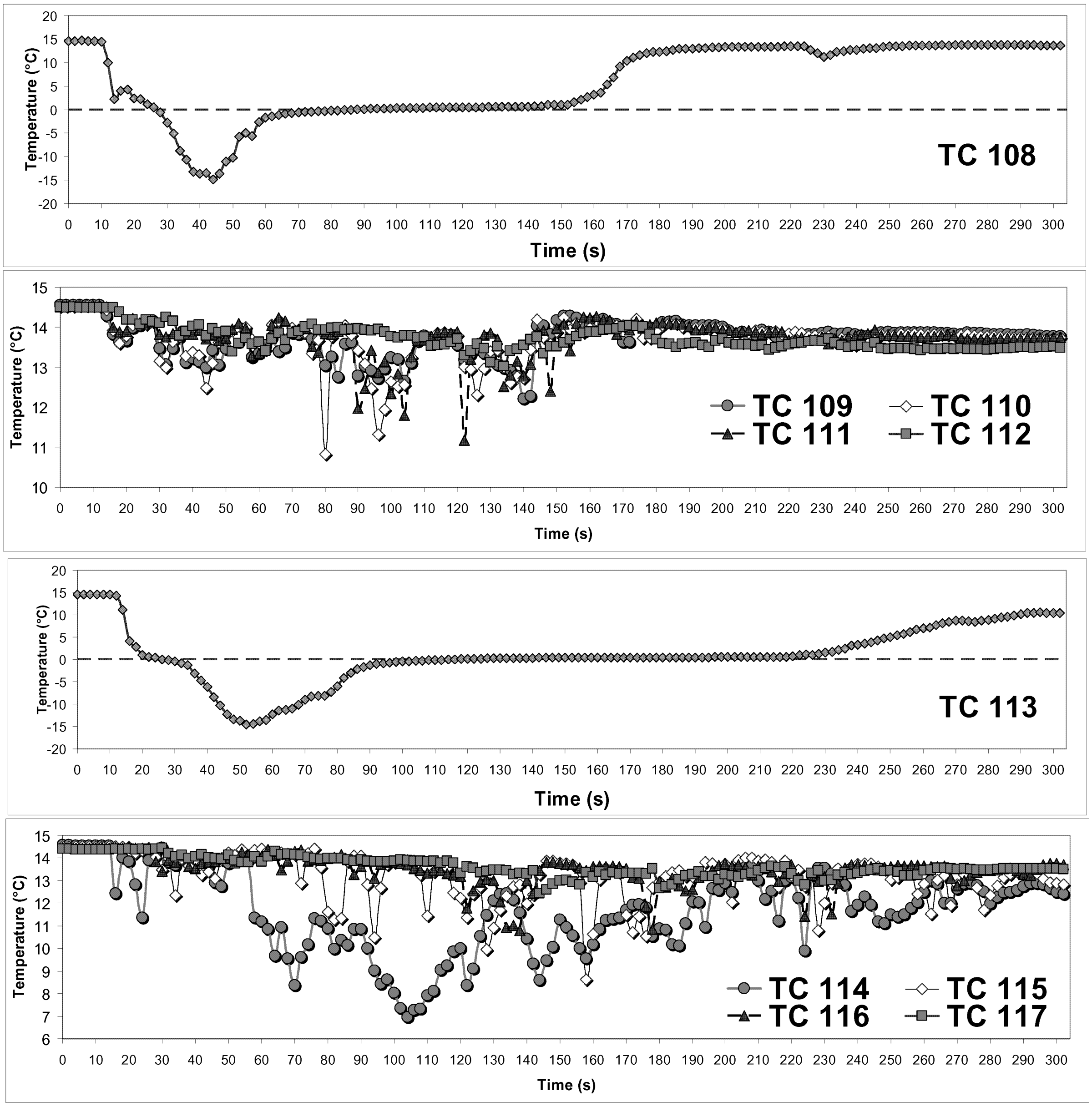

Fig. 7:. Temperature trends for TC 108,113 (dashed line evidences 0°C), TC 109-110-111-112 (window 3), TC 114-115-116-117. Temperatures are in °C, time in s.

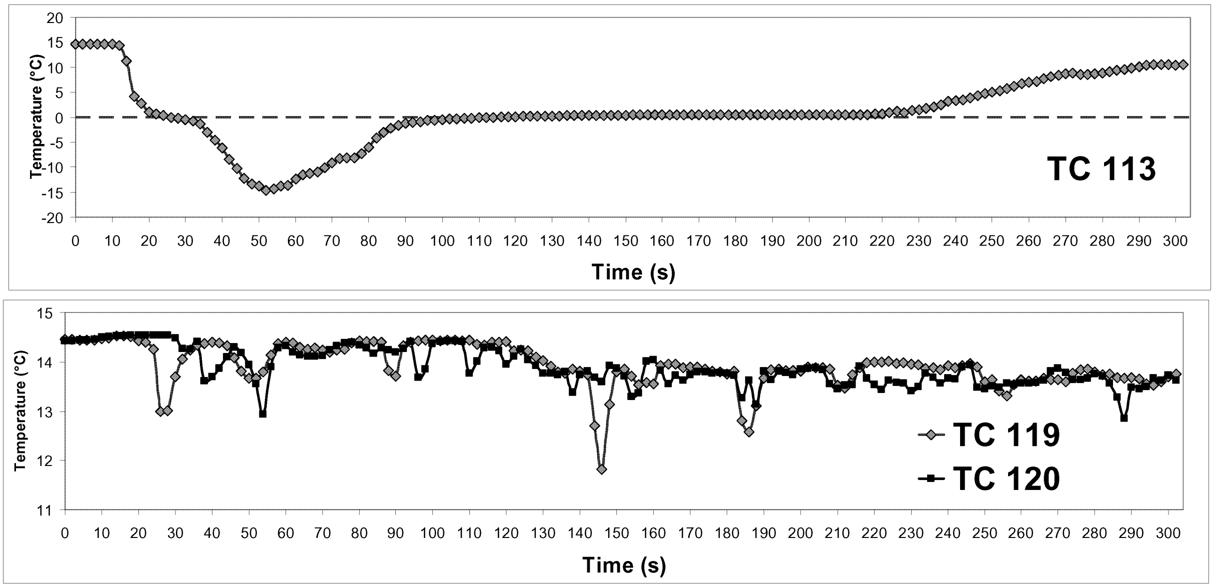

Fig. 8:. Temperature trend for TC 118 (dashed line evidences 0°C), and TC 119-120 (window 5). Temperatures are in °C, time in s.

4. MODELLING OF EXPERIMENTAL RESULTS

In order to make preliminary considerations on experimental data, a schematization of heat fluxes and heat transfer contributions has been made, as reported in Figure 9.

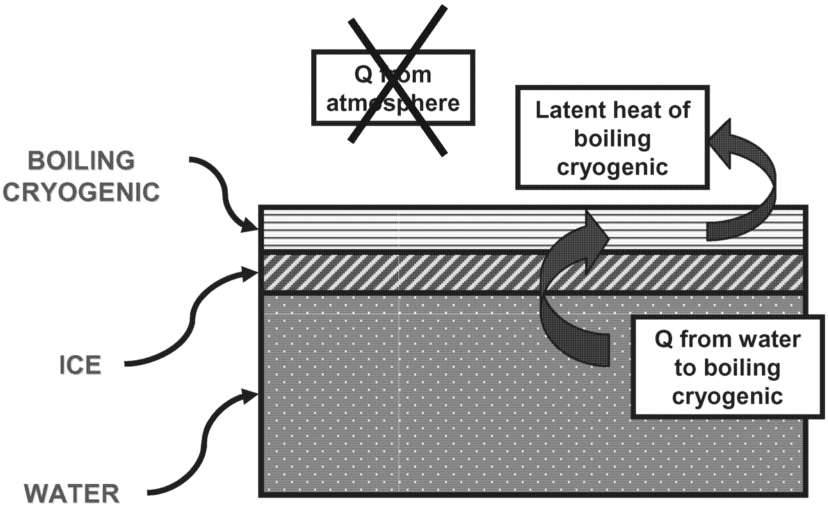

Fig. 9:. schematization of the thermal balance of the experiment, neglecting the heat exchanged with the surrounding environment.

4.1 “Classic” Fourier conduction model

As first step, a comparison between “classic” Fourier equation and experimental data has been made. The equations have been solved for some initial conditions (corresponding to different experimental runs) in order to compare temperature trends and ice thickness. Comparison between Fourier and experimental data shows two clear evidences:

I) Ice thicknesses from Fourier model are much larger than experimental ones. Experimental values (evaluated both from temperature trends and visual observations) are around 5 mm, even lower for shorter releases, while modelled thicknesses are far above 10 mm

II) Surface temperatures are much higher than 77 K (i.e. boiling temperature of liquid nitrogen)

The latter evidence can be explained with the above-mentioned superheating of vapour film during boiling, while the former issue may be related to the convection contribute, which is neglected by Fourier model.

At this point modelling activity follows two approaches: a more detailed conduction model [8] and a simplified model considering both conductive and convective heat transfer.

4.2 Conductive detailed model

The model considered was developed Conrado &Vesovic (2000) for LNG releases onto water, and it has been fitted with the results of the present experimental device. The main aspects of the model can be summarized as follows:

- Only conductive heat transfer is considered;
- Model is one-dimensional;
- The temperature of water surface is not constant, but changes as heat transfer proceeds;
- Model takes into account phase change between liquid water and ice;
- Differential equations are solved by a finite differences methodology (Kuateladze 1952), in which ice and liquid regions are divided into a number of nodes.

Since only conductive heat transfer is considered, an overall fitting coefficient, which takes into account both conduction and convection is implemented in the model. Therefore the model can be used to obtain the interpretation of experimental runs, which show a good agreement with the model results imposing a superheat of 40 K and a heat transfer coefficient of about 100 W/m2K. This evidences the relative importance of the convective contribution to the heat transfer.

4.3 Simplified model

As explained above, the model used to fit experimental data is a conduction model, in which convection contribute has been neglected (obtaining actually a good agreement).

In order to evaluate in a simple way convection contribute, we can write a heat balance to estimate convection contribute in heat transfer (see Figure 14).

$$Q_{cond} + Q_{conv} = Q_{lat} + Q_{ice} \tag{1}$$

i.e. heat given by water (both with conductive and convective mechanism) is equal to the one given by ice formation and undercooling.

As we know water/ice temperature during the whole release and the conductive contribution to heat transfer, estimated by applying conventional conduction models (see section 4.1 and 4.2), we can estimate the net convective contribution. Comparing experimental results to literature values of convective heat transfer coefficients, it results that experimental heat transfer coefficients are much greater than literature ones (more than one order of magnitude), thus testifying the strong presence of convection inside the liquid water bulk.

5. CONCLUSIONS

An experimental facility was realized in order to study the LNG spill spreading onto water surfaces. A Plexiglas pool equipped with thermocouples, in which cryogenic nitrogen releases have been realized, in still and wavy water conditions. Temperature profiles along water depth have been obtained, during cryogenic release and pool boiling.

Experimental data have collected in order to provide further support to modeling of pool spreading, identifying the possible convective contributions to the evaporation.

An ice layer forms on water surface, with variable thickness depending on experimental conditions (ambient and water temperature, release rate and duration) which gives a rate of sensible heat while sub cooling.

Boiling regime has been pointed out, resulting film boiling, with an overheating of vapor film, decreasing during cryogenic boiling. After comparing experimental data with classic Fourier model, a detailed conduction model has been fitted and applied to experimental data. Modeling was aimed at understanding heat transfer mechanism, and if convection plays a relevant role. From comparison between modeled and experimental data it was evident that the convective contribution plays an important role for the evaluation of the heat transfer between water and the released cryogenic.

6. REFERENCES

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