Enhancing Cooling Capabilities of Spray Cooling using Salt Solution

Zil Shoikhetbrod[1], Alex Koyfman[2,3], Gedalya Mazor[2], Izhak Ladizhensky[2], Merav Arogeti*[2]
[1]Department of Green Engineering, Sami Shamoon (SCE), Be'er Sheva, Israel.
[2]Department of Mechanical Engineering, Sami Shamoon (SCE), Be'er Sheva, Israel.
[3]Nuclear Research Center Negev, Dimona, Israel.
*Corresponding author: meravar@sce.ac.il

Abstract
A known fact is that a drop falling on a very hot surface, above Leidenfrost temperature, evaporates very slowly; thus, the surface heat losses at a small rate. Therefore, spray cooling does not consider an efficient cooling method. However, there are some cases in which spray cooling is the only possible way to remove heat. Among these cases are burning accidents of industrial facilities, in which many metal surfaces reach very high temperatures, Loss of Coolant Accident (LOCA), and Loss of Flow Accident (LOFA) that happened in the FUKUSHIMA disaster. During this disaster, the Japanese firefighters used seawater for the reactor spray cooling in an effort to prevent the reactor core from melting. The seawater as coolant was the motivation for this study, to learn the influence of salt concentration in water solutions on heat transfer coefficient during spray cooling of hot surfaces.
The impact of salt concentrations on heat transfer coefficient studied experrimentaly. The experiments were performed by spraying two types of water-salt solutions on hot surfaces and measuring the temperature drop rate. The solutions were water - magnesium sulfate and water - calcium chloride at different concentration ratios. The experiments showed that higher salt concentrations have better heat transfer performance.

This template illustrates the formatting of full-length papers for ILASS 2022 proceedings. Please do not change any formatting, such as margins. The abstract should be no longer than 150 words. (regular text will be Arial 11 with 1.15 line spacing in all parts and sections of the manuscript)

Keywords
Heat flux, Surface tension, boiling heat transfer, Magnesium sulfate, Calcium chlorid

Introduction
Extreme cases such as the disaster in Fukushima nuclear power station, encourage the study of heat transfer enhancement. One of the methods to enhance heat transfer from hot bodies is surface enhancement. This method used in heat exchangers by altering the heat exchanging surface by means of geometric shapes such as ribs, grooves, coils and porosity on the surface [1]. Another method to increase the heat transfer coefficient from surfaces is by using different coating layers made of nanoparticles [2,3]. In this work we examined effect of alternately surface enhancement on the heat flux from the surface. The surface enhancement performed by forming different structures of salt on the hot surface. Work [4] done by a group from Florida University showed that hydrophilic coating of TiO2 and silicone oxide enhance boiling heat transfer.

The goal for this work is investigation of heat transfer enhancement of spray cooling boiling heat **transfer** buy means of salts additives.
Adding magnesium sulfate and calcium chloride to water changes the thermophysical properties of the solution, mainly the surface tension. Surface tension controls the wetting angle and the drop size created by the dye of the sprayer. According to Rohsenows nucleate boiling correlation equation (Eq. 1) surface tension in one [5,6] of the parameters affecting the boiling heat transfer.

$$\frac{c_p \cdot \Delta T_b}{h_{fg}} = c_{sf} \cdot \left[\frac{q''}{\mu \cdot h_{fg}} \cdot \sqrt{\frac{\sigma}{g \cdot (\rho_l - \rho_g)}}\right]^m \cdot \left(\frac{c_p \cdot \mu}{k}\right)^n \qquad (1)$$

Material and Methods

The surface tension of the solution used was measured by the pendant drop method (Figure 1). We used six solutions of distilled water mixed with magnesium sulfate and calcium chloride (at concentrations various concentration ratios). For each solution we conducted several series of experiments were done, total of three experiments for each solution and each experiment included five tests, in order to obtain maximum accuracy in the experimental results. The surface tension of distilled water was measured for calibration test of the experimental apparatus and as a reference value for the solutions.

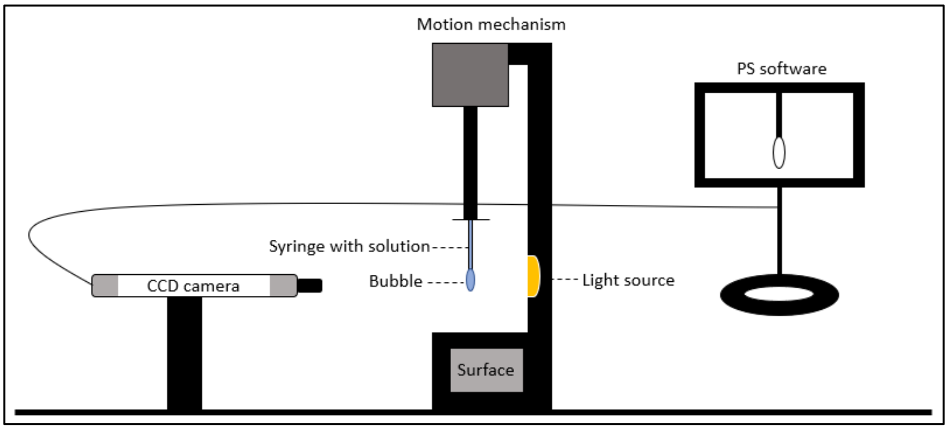

Figure 1 - surface tension measurement apparatus

The heat flux measurements apparatus (Figure 2) was built from a steel (1030) plate, heated to temperature of $600°C$ in which 4 thermocouples were inserted as shown in Figure 2 . After reaching the setup temperature solution was sprayed on the steel plate cooling the plate. The thermocouples reading was recorded vs time. Measuring the temperatures on both sides of the surface enables us to calculate the heat flux along the process.

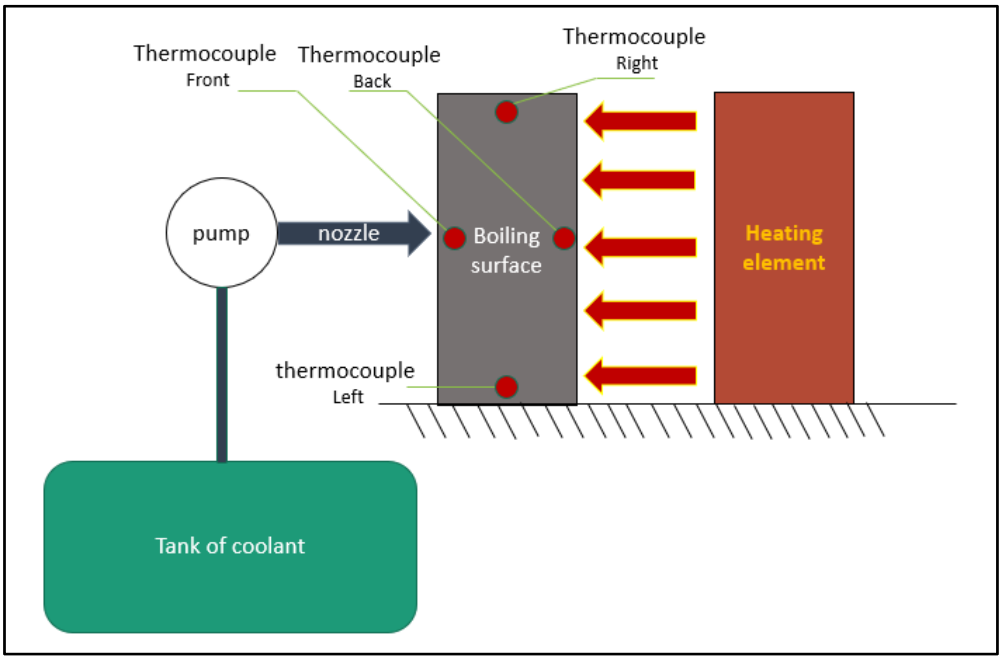

Figure 2 - The heat flux measurements apparatus

Results and discussion

Heat flux experiments on a boiling surface

We conducted a Set of experiments, spraying different salt solution on heated surface. The solution boiling water evaporated on the hot surface and left a temporary porous salt layer on the hot surface (**שגיאה! מקור ההפניה לא נמצא.**). The layer crystalline structure changes distribution and thickness are not homogenous on the surface. The changes occur along the cooling duration as we spray more salt solution. In addition to the layer changes during the cooling process, higher solution concentration increases the layer density (see **שגיאה! מקור ההפניה לא נמצא.**).

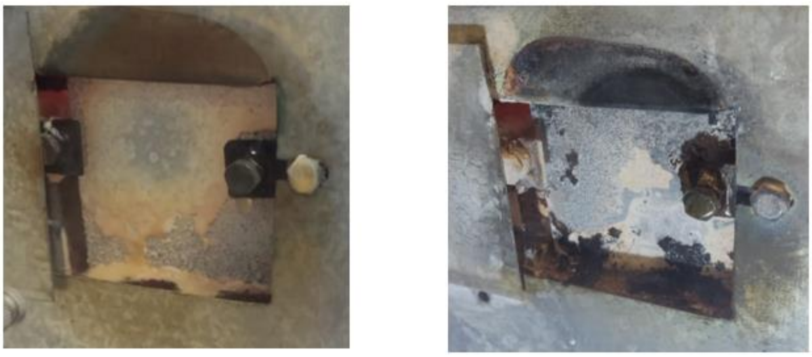

Figure 3 - Crystalline structure on the hot surface MgSO4 15% (left) and MgSO4 10%(right) The layer structure enhanced the heat flux, during spraying the boiling surface.

The solutions with the best results for heat flux experiments, compared with the performance of the seawater ($NaCl$ 3.5%) solution, the coolant that used for cooling the reactor in the Fukushima disaster and plain water. The magnesium sulfate solution at a concentration of 15%, shows the best heat flux results, at the beginning of the cooling process (temperatures range of about 550-450℃), when the maximum value reaches about 250,000 $[\frac{W}{m^2}]$, and then stabilizes around constant value of heat flux which is a bit more than 200,000 $[\frac{W}{m^2}]$. However, calcium chloride solution at concentration of 30%, shows the best results for heat flux for temperatures range of about 400-200℃, maximum heat flux value reaches about 240,000 $[\frac{W}{m^2}]$. the plain water and the seawater heat flux value is less than half, with light increase under the boiling point, $100°$ (see Figure 5).

Solutions surface tension measurements

The surface tension experiments indicate a light systematic reduction in the surface tension as the salt concentration increases, the total measured reduction was less than 6% between the different concentrations. The surface tension values for both examined salts the Magnesium Sulfate and Calcium Chloride are similar (Figure 4). For example, in a concentration of 5% calcium chloride we obtained a surface tension whose majority of samples are in the ranges of 72-72.8 $[\frac{mN}{m}]$, and so also for the surface tension results of magnesium sulfate (in the same concentration). If we are looking at magnesium sulfate and calcium chloride solutions in concentrations of 10% and 15%, then the results of surface tension for them are reaching to the ranges that are around 70-71 $[\frac{mN}{m}]$ and 68.5-69 $[\frac{mN}{m}]$ respectively.

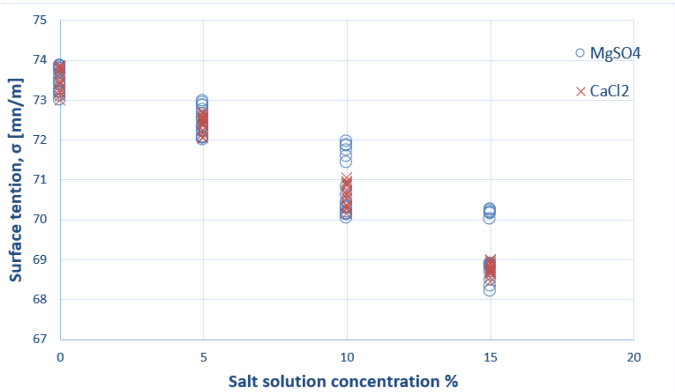

Figure 4 - surface tension measurements

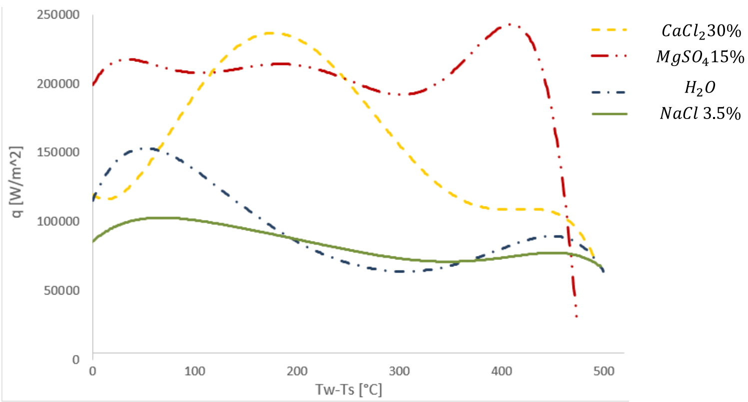

Figure 5 - typical heat flux experiment results

Conclusions

the results of this study showed that magnesium sulfate solution in concentration of 15% generates a stable heat flux along the cooling process. The magnesium sulfate at least doubles the water and seawater heat flux for cooling high temperatures. Second in line is the calcium chloride solution in concentration of 30%. The experiments demonstrate that the formation of homogeneous crystalline structures on the surface increases the rate of heat removal from the surface and increases the surface heat flux respectively. The effect of layer adhesion and distribution on the surface as well as the influence of surface tension and wetting angle at elevated temperature on the heat removal from hot plats requires further study.

References

[1] C. Maradiya, J. Vadher, R. Agarwal, The heat transfer enhancement techniques and their Thermal Performance Factor, Department of Mechanical Engineering, L.E. College, Morbi 363641, India, Received 5 January 2017.
[2] E. Forrest, E. Williamson, "Augmentation of nucleate boiling heat transfer and critical heat flux using nanoparticle thin-film coatings", Department of Nuclear Science and Engineering, Massachusetts Institute of Technology, USA (2009).
[3] R. K. Iler, "MULTILAYERS OF COLLOIDAL PARTICLES", The Industrial & BiochemicaIs Department, Wilmington, Delaware (1965).
[4] W. Wu, H. Bostanci, "Nucleate boiling heat transfer enhancement for water and FC-72 on titanium oxide and silicon oxide surfaces", Department of Mechanical, Materials and Aerospace Engineering, University of Central Florida, Orlando, USA (2009).
[5] J. M. Saiz Jabardo, "Evaluation of the Rohsenow Correlation Through Experimental Pool Boiling of Halocarbon Refrigerants on Cylindrical Surfaces", Department of Mechanical Engineering, University of Sao Paulo, Brazil (2004).
[6] I.L. Pioro, "Experimental evaluation of constants for the Rohsenow pool boiling correlation", Department of Mechanical Engineering, University of Ottawa, Ottawa, Ontario, Canada (1998).

Nomenclature

c_p	specific heat	$[kJ \cdot kg^{-1} \cdot ℃^{-1}]$
ΔT_b	Excess Temperature	$[℃]$
h_{fg}	Fusion enthalpy	$[kJ \cdot kg^{-1}]$
C_{sf}	Constant	
q''	Heat flux	$[w \cdot m^{-2}]$
μ	Viscosity	$[N \cdot s \cdot m^{-2}]$
g	Gravitational acceleration	$[m \cdot s^{-2}]$
σ	Surface tension	$[N \cdot m^{-1}]$
ρ_l	Liquid density	$[kg \cdot m^{-3}]$
ρ_g	gas density	$[kg \cdot m^{-3}]$
k	Thermal conductivity	$[w \cdot m^{-1} K^{-1}]$
m	Constant	
n	Constant	