Numerical simulation of cooling and freezing processes for the cryopreservation of biological material in liquid nitrogen

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ABSTRACT

The knowledge of the cooling and/or freezing rates in a biological sample during cryopreservation procedures is of major importance. Specifically, the measurement of temperature changes in the sample can be used to determine whether a sample is vitrified or undergoes phase transition. When dealing with liquid nitrogen (LN), having a saturation temperature at atmospheric pressure, T_{sat}= -196 ºC, the temperature difference between the fluid and the sample (which can be at room temperature), is large enough to cause boiling of LN, entering into the film boiling regime [1]. This determines a heat flux from the object to LN causing the latter to boil in the immediate vicinity of the object and creating a pocket of nitrogen vapor around the object which acts as an “insulator” and retards further heat transfer. Film boiling is also referred to as the “Leidenfrost effect”. Boiling curves for a specific cryobiological system are scarcely found in the literature due to the small dimensions of the devices used in the process and the experimental limitations. The boiling curve which corresponds to variation of the heat flux (q) as a function of the excess wall temperature ($\Delta T=T_{wall}- T_{sat}$) depends on several relevant factors such as: i) the type of cryogenic fluid used and its thermal properties, ii) the material in contact with the fluid and its roughness which affects the nucleation sites and the Leidenfrost Temperature, iii) the relative position of the solid in the cryogenic fluid (vertical, horizontal, or in angle), and iv) the geometry of the solid (plates, sphere, cylinders, or irregular shapes) [2]. In this work the different heat transfer coefficients of straws filled with ice were experimentally determined by measuring time-temperature curves when they were immersed in LN; this allowed to observe the existence of different boiling regimes. The application of a numerical finite element program using the software COMSOL was used to predict the time-temperature curves and to obtain the surface heat transfer coefficients corresponding to each boiling regime. Independent experiments were carried out using straws that contained a biological fluid (semen+extender) which undergoes a phase change transition (freezing), to further validate the surface heat transfer coefficients for film and nucleate pool boiling. The program takes into account the variable thermo-physical properties of the biological sample; this constitutes a highly non-linear mathematical problem. Additionally the numerical program allowed the determination of the range of ΔT where each regime develops, and the Leidenfrost temperature where the transition of film into nucleate pool boiling regime occurs. A good agreement was obtained between the experimental temperature profiles and the numerical predictions during cooling of straws containing both ice and bovine semen + extender, confirming the reliability of the numerical results. Moreover, these results were corroborated with literature correlations in terms of dimensionless numbers. The numerical program is an important tool in order to correctly assess the heat transfer process and optimize the cryopreservation of straws filled with biological fluids.

REFERENCES

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