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Physical modeling of flow boiling in microchannels and its induced vitrification of biomaterials

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ABSTRACT

Vitrification preservation is a promising approach for long term storage of biomaterials (e.g. cell suspension) by avoiding intracellular ice formation, and ultra-fast cooling is the key factor to achieve vitrification. In this study, a novel cooling system is introduced and investigated. Physical processes, including flow boiling of liquid nitrogen in microchannels as well as cooling and solidification of the film-shaped sample solution in the system, are theoretically modeled. By simulating the local cooling rate and degree of crystallization in sample solution, the cooling performance of the system is evaluated. Case studies indicate ultra-high cooling rates and high vitrification tendency of sample solution are promisingly achieved with such system. Furthermore, the system dimensions can be adjusted in a flexible range to allow preserving of various volumes of samples. In conclusion, the novel cooling system will hopefully decrease the required concentration of cryoprotectant for vitrification and extend the application area of vitrification preservation, and the model presented in this study can be a useful tool to guide the design and application of such system.

1. Introduction

Vitrification implies the phase transition of a liquid to a glass with a very low degree of crystallization [1,2]. Recent research reveals that vitrification is an effective approach to preserve various biomaterials by avoiding intracellular ice formation [3–7]. In particular, vitrification is regarded as the only feasible way to successfully cryopreserve some human cells and tissues such as oocytes and brain tissue [3,8].

Ultra-fast cooling is the key to complete vitrification. To achieve high cooling rate, a variety of systems and methods have been developed [3–12], most of which involve a process of immersing a mini volume of sample (with or without a carrier) into liquid nitrogen [3–7,9,11]. Although these methods have been well used in some areas, they are still far from perfect especially from the point of view of heat transfer principle. Firstly, the direct plunging of high temperature sample into liquid nitrogen results in strong boiling and vaporization of liquid nitrogen around the sample surface, and forms a "vapor coat" which acts as a heat-insulation layer [11,12]. As a result, the heat transfer coefficient (h) is limited ($<10^3$ W/m^2 K) [12]. Secondly, the geometries of the samples in these methods are generally cylindrical or spherical, which limit the ratio of the sample surface versus its volume. As a result, heat conduction inside the samples significantly lowers the cooling rates. Given the disadvantages, current vitrification preservation systems still have significant limitations, such as high concentrated cryoprotectant (CPA) is required and the capable sample volume is often restricted to micro- or nano- liters, and so on.

Aiming to provide more effective vitrification preservation, a novel system which utilizes an advanced heat transfer principle, i.e. microchannel heat transfer, was proposed in our previous work [13]. Microchannel heat transfer was initially proposed by Tuckerman and Pease in the early 1980s and has now been demonstrated as an effective mean for dissipating large amount of heat from high-flux devices in a variety of computer and aerospace applications [14–16]. Especially when phase change occurs in microchannels, the two-phase heat transfer coefficient can be as high as 10^{5-6} W/m^2 K [15–18]. Therefore, flow boiling in microchannel is believed to be an ideal solution to achieve significantly higher cooling rate.

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Nomenclature

c_p	specific heat
D_h	hydraulic diameter
h	heat transfer coefficients
H	channel/wall height
k_a	correlation constant
k	thermal conductivity
L	length of sample layer
L_c	latent heat of liquid nitrogen
L_h	latent heat of water
m	fin parameter
Nu	Nusselt Number
p	pressure
Pr	Prandtl number
q	heat flux
Q	activation energy
R	gas constant
Re	Reynolds number
S	heat source term
t	time
T	temperature
v	volume fraction
W	channel/wall width
x	distance *in x* dimension
x_e	thermodynamic equilibrium quality
y	distance *in y* dimension

Greek symbols

β	ratio of channel depth to width
ρ	density
δ	thickness of sample layer
Δx	grid space in x dimension
χ	degree of ice crystallization
η	fin efficiency
μ	viscosity

Superscripts/subscripts

h	water
m	melting
f	fluid
l	liquid phase
v	vapor phase
s	solid phase
w	chip wall
ch	channel
sp	single phase
tp	two phase
nb	nucleate boiling

As shown in Fig. 1, when a thin frame is adhered between two pieces of chip wall, a micro cavity will be formed inside. Once cell suspension (sample) is injected into the cavity, it will be kept as a thin film. In this manner, a high ratio of sample surface versus its volume can be achieved. On the outer surface of each chip wall, microchannel array is etched to allow working fluid (e.g., liquid nitrogen) and enhance the heat exchange efficiency. As might be imagined, once liquid nitrogen enters the channels, abrupt flow boiling will occur, and the sample solution will be rapidly cooled down.

Due to the tiny sample volume and the ultra-fast cooling process, experimental study is very difficult for a vitrification system to examine its cooling rate. Some experiments had been performed [12], but only the cooling histories at certain locations in the sample can be monitored. Actually, temperature distribution is quite non-uniform in the ultra-fast cooling processes, and the recorded cooling rates are usually not sufficient to evaluate the overall cooling performance. Therefore, theoretical analysis is required and had been performed for some recently developed systems [10,11]. For the novel system introduced herein, a simple one-dimensional model was proposed in our previous work, which assumed the axial temperature distribution is uniform and the value of h in the micro-channel is a known constant [13]. This preliminary study demonstrated the novel system should be effective to achieve ultra-high cooling rate, but the over-simplified model cannot provide enough information for system evaluation and design. Therefore, the purpose of this study is to revisit the physical processes in the system and then develop a more accurate model to critically evaluate the system capacity, e.g., the magnitude of cooling rate and the flexibility in preserving various volumes of samples, and guide the design and application of such system hereafter.

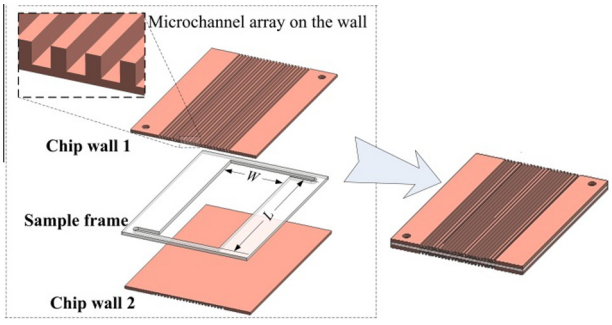

Fig. 1. A concept design of the microchannel cooling system.

2. Method of approach

Considering the symmetric and periodic structure, a unit cell of the system is modeled as illustrated in Fig. 2. The computational domains can be de a divided into a flowing subdomain (in one dimensional, x), i.e., the fluid field in microchannel, and a stationary subdomain (in two dimensional, x and y), including the chip base under the channel and a half of the sample frame and sample solution under the chip base. On the interface between the two subdomains, there is a heat flux from chip wall to working fluid due to the temperature difference. Consequently, the cryogenic fluid is heated and flow boiling occurs in the flowing domain, and simultaneously the stationary domain is cooled and solidification (crystallization or vitrification) of the sample solution may occur depending on the cooling rate. Those processes are theoretically modeled as follows.

2.1. Modeling of the processes in the flowing domain

In the presented system, there may be both two-phase flow region and single-phase flow regions in the microchannel. The usual approach to the modeling of multiphase flow in microchannels is to compute the evolution of the gas–liquid interface, and the homogeneous assumption is often made for the velocity and temperature fields [19]. Based on the homogeneous assumption, all the two phases of fluids are assumed be strongly coupled and