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Experimental Thermal and Fluid Science 30 (2006) 821–828
Experimental Thermal and Fluid Science
www.elsevier.com/locate/etfs

Integrated microthermoelectric cooler for microfluidic channels

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Abstract

Precise fluid temperature control in microfluidic channels is a requirement for many lab-on-a-chip and microreactor devices, especially in biotechnology where most processes are highly temperature sensitive. We demonstrate the concept of a microthermoelectric cooler integrated into a microfluidic channel in order to give rapid and localised fluid cooling. The key aspect of this concept is the use of a second imbedded microfluidic channel that is used as a miniature heat sink. An analytical thermal model has been derived that couples thermoelectric effects with fluid heat-transfer rates from both the hot and cold connections. Using this model, the effect on cooling performance of varying the thermal resistance between the hot and cold connections and the fluid has been quantified, as well as the effect of substrate thermal conductivity. If the substrate thermal conductivity is too high, heat leakage renders the thermoelectric cooler ineffective. The optimum electrical current for cooling has been shown to be a function of the thermal resistance of the heat sink. For thermoelectric coolers there is competition between temperature reduction and cooling power. Using this fact, based on the final fluid temperature required, we have calculated the maximum flow rate that will achieve this. Finally, a prototype integrated microthermoelectric cooler has been fabricated and tested.

Keywords: Thermoelectric cooler; Heat transfer; Microfluidics

1. Introduction

For lab-on-a-chip, microreactors and biochip devices it is often imperative to control the temperature of minute amounts of fluid so that reactions may be controlled, sensors and actuators stabilised and biomolecules manipulated. Microheaters integrated with microfluidic channels have been around for some time and involve using photolithography to pattern resistive metal heaters, which may be a few hundred nanometres thick and tens of microns wide, on a substrate ([1,2]). Microheaters are of limited use for temperature control as they can only be used for raising the fluid temperature. Additionally they are limited in creating large thermal gradients (in the order of 10 K/mm [1]) due to thermal conduction in the substrate tending to smooth out the temperature gradient. In order to provide full temperature control and higher temperature gradients, cooling is required. Active cooling such as compression-based refrigeration requires sophisticated engineering of moving parts that is impractical on the microscale. Alternative cooling methods have been proposed, such as using endothermic reactions in microchannels, but this method lacks precise control [3] or thermoacoustic refrigeration, which is still far from a viable working device [4]. One method that scales well on the microscale is thermoelectric cooling [5], that utilises the Peltier effect at the junction between two dissimilar materials. Using the Kelvin relations, the magnitude of Peltier cooling ends up being proportional to a material property called the Seebeck coefficient, the current and the temperature [6].

There has been much interest in the material science of thermoelectric devices, in developing new materials that have high Seebeck coefficients to increase thermoelectric cooling, low thermal conductivity to avoid heat leakage and high electrical conductivity to minimise Joule heating. Recently, nanostructured materials have shown a dramatic

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doi:10.1016/j.expthermflusci.2006.03.011

Nomenclature

α	difference between two thermo-element's Seebeck coefficients (V/K)
κ	thermal conductivity (W/K m)
ρ	electrical resistivity (Ω m)
A	cross-sectional area (m^2)
c_p	specific heat (J/kg K)
D_h	hydraulic diameter (m)
h	convective heat transfer coefficient (W/m^2 K)
H	height of thermoelements (m)
I	current (A)
K	net thermal conductance (W/K)
$\dot{m}$	mass flow rate (kg/s)
n	number of thermoelectric pairs
Nu	Nusselt number $= hD_h/\kappa_{fluid}$
Pr	Prandtl number
q	heat transfer rate (W)
R	resistance (K/W or Ω)
Re	Reynolds number based on hydraulic diameter
T	temperature (°C)
z	axial distance in channel (m)
z^*	non-dimensional axial distance in channel

Subscripts

a	ambient
c	cold connection
elec	electrical resistance
f	fluid
g	generated heat
h	hot connection
hs	heat sink
p	Peltier elements
s	substrate

increase in thermoelectric figure of merit [7,8], which will lead to the availability of much more efficient devices. As yet, however, there has been little effort in determining the issues associated with integrating thermoelectric coolers onto microfluidic channels for local temperature control.

Small thermoelectric coolers with centimetre dimensions have successfully been used to help remove the heat from high power-density IC chips or to control and stabilise substrate temperatures [9]. These devices generally require large external air-cooled heat sinks to dump the heat generated, much like the heat sink and fan used for cooling current personal computer CPUs (see for example [10]). There have been attempts to incorporate water-cooled channels for heat-sinking thermoelectric coolers for ICs [11], but again these are relatively large and bulky and unsuitable for lab-on-a-chip devices. For lab-on-a-chip devices it is generally not practical to incorporate large external heat sinks to remove the heat from the hot side of a thermoelectric device, although external thermoelectric coolers have been successfully retrofitted to an electrophoretic chip along with the heat sink and external cooling fan [12]. This method offered bulk cooling to the channels and response times in the order of seconds.

New microthermoelectric devices are being developed with microsystem fabrication technology with approximately 100 devices in parallel, in an area of about 1 mm^2 [13]. Microthermoelectric coolers with similar dimensions have been designed and fabricated for temperature control for mini lasers [5,14], to actuate an ice valve for microfluidic systems [15], and for microvapour sensors [16] with response times in tens to hundreds of milliseconds.

In this paper, we propose the use of an integrated thermoelectric cooler to control fluid temperatures in microchannel flow, and, in order to avoid the use of bulky heat sinks, to use a second microfluidic channel perpendicular to the cooled channel to convect the heat away from the hot side. The concept involves minimising thermal resistance by having liquid flow directly over the thin silicon hot connection, and increasing convective heat transfer coefficients by using liquid instead of gas flow. The basic layout is shown in Fig. 1. This configuration offers many advantages over cooling with a simple cross-flow arrangement, such as very precise, localised and rapid temperature control, the ability to rapidly change between heating and cooling by reversing the current direction, and increased efficiencies due to the minimal thermal resistance between the heat source/sink and the target fluid. This arrangement may be ideal for rapid PCR, for example, where a series of Peltier elements arranged along a channel with alternating heating and cooling would allow tens of millisecond cycle times.

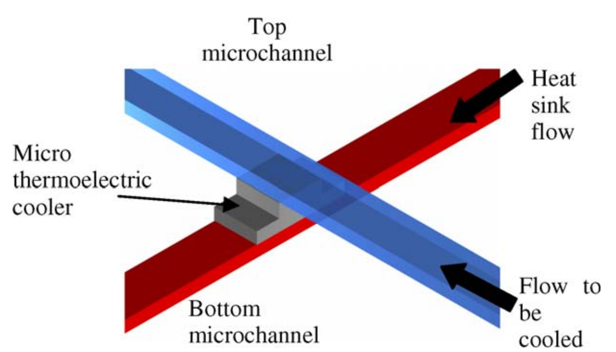

Fig. 1. Schematic diagram of integrated thermoelectric cooler concept.

In this paper, a one-dimensional model is developed in order to quantify design issues associated with integration of a thermoelectric cooler, and a fabrication method for prototyping is presented.