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An internal penalty discontinuous Galerkin method for simulating a thermoelectric cooler

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ABSTRACT

Compact modelling of a thermoelectric cooler in the computational fluid dynamics approach is essential for reliable product design in the telecommunication industry, particularly for the package design of the optical laser or the wavelength selective switch. When simulating these fluid thermal structure interaction problems numerically, stability and high order of accuracy are required to capture all of the necessary physics. The principle benefit of using the discontinuous Galerkin (DG) method is that it can produce a high order accurate scheme which can achieve an equivalent error compared to the lower order scheme with orders of magnitude lower computational effort. Based on the recent development of a framework for the computation of fluid thermal structure interaction problems within multi-solid domains using DG methods on unstructured grids([1,2]) ; this paper has proposed a detailed compact thermoelectric cooler (TEC) modelling method based on an existing black box like compact TEC model [4]. Close comparisons validate that both the detailed and the black box like compact model are accurate enough to simulate the conduction only case. When air convection is required to carry out a system-level thermal management optimization, the detailed compact modelling method is more reliable than the black box like compact TEC model. Furthermore, the thermal expansion of an operating TEC has been examined. Compared to the black box like compact TEC model, the simulation results of the detailed compact method have better agreement with electronic speckle pattern interferometry data.

1. Introduction

Thermal management plays a significant role in the design of optical modules. The primary objective of the optical package design is to reduce the package size to fit into the line card level. The standard height requirement for a single slot line card is usually within 20–30 mm. This restrictive height budget necessitates a compact package design. As a result, the integration of an efficient and compact temperature control system into the optical package becomes the key driver during optical system design. A traditional cooling system such as fans or water cooling systems all require $\geqslant$ 10 mm installation height which is far above the design height budget. Due to its compact size and precise temperature control capacity, a thermoelectric cooler (TEC) is usually employed as the primary temperature control component inside a laser or optical switch package.

The simulation of the thermal performance of an operating TEC inside the optical package can be cataloged as the case of analyzing the effect of solid conduction on conduction/convection heat transfer through the fluid inside the enclosures. This problem has received significant attention due to its important applications in many science and engineering fields. Du and Bilgen investigated the effect of various parameters on conjugate heat transfer in a rectangular cavity and concluded that the heat transfer is dominated by conduction for a large conductivity ratio and solid wall width whereas fluid convection is only intensified at lower values [9]. Mobedi analyzed the influence of Rayleigh number and conductivity ratio of a finite thickness horizontal wall within the cavity [18]. Varol and Oztop et al. studied the conjugate heat transfer via natural convection and conduction in the triangular enclosure filled with porous media [24]. Sheikholeslami and Seyednezhad et al. investigated the effect of Lorentz force on nanofluid natural convection inside a porous cavity with different geometry. Roles of the solid-nanofluid interface heat transfer parameter, Hartmann number, porosity and Rayleigh number had been carefully investigated [22,23].

A TEC, sometimes referred as a thermoelectric module or Peltier cooler, is a semiconductor-based electronic component that functions as a small heat pump. The principle of thermoelectric cooling

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dates to the discovery of the Peltier Effect by Jean Peltier in 1834. Excluding Joule heating which accompanies all electric current, Peltier observed that when an electric current passes across the junction of two dissimilar conductors, depending on the direction of the current, the overall effect could be either heating or cooling. This effect can be harnessed to transfer heat, creating a heater or a cooler. In practice, TECs are constructed using two dissimilar semiconductors, one n-type and the other p-type. The two semiconductors are positioned thermally in parallel and joined at one end by a conducting cooling plate. The heat pumping capacity of the TEC is proportional to the operating current and the number of pairs in the module. When a DC passes through the TEC module, heat will be moved through the module from one side to the other. This phenomenon can be reversed by a change in the polarity of the applied DC voltage. TEC has advantages of high reliability, no moving mechanical parts, compact size and light in weight. In the industry of fibre-optic communications, the TEC module is widely used for precise temperature control applications thereby making it highly suitable to be integrated into an optical package [14].

A cross-sectional view of a typical laser package is shown in Fig. 1. The module consists of a laser diode (LD) chip, a submount onto which the LD chip is soldered, optics that couple the laser beam from the LD chip to an optical fibre and a TEC. It is mandatory that the optical and electronic parts are aligned with the highest precision to ensure the light path. For a precisely aligned optical system, even micron level deformation on core optical components will misalign the full optical path, resulting in instability in wavelength. On the other hand, a compact package layout is essential to meet the height budget of the line card design. This can lead to a significant heat flux around TEC area, which will introduce large temperature gradients on the individual optical component, resulting in the degradation of optical system performance as demonstrated experimentally by Chang and Wang [3]. Fig. 2 shows electronic speckle pattern interferometry (ESPI) measurements of real-time whole-field thermal deformation. When a DC is applied, the temperature gradient produced between two ceramic plates can cause thermal strain, which bends the optical bench bonded on top.

A TEC consists of n-type and p-type thermo-elements with the top and the bottom substrate mounting as shown in Fig. 3. Based on this structure, a typical modelling approach is to construct the model at element level with the assumption that the p and n elements have the same material properties. Based on this assumption, recent research focusses on two TEC thermal performance modelling strategies, (i) a detailed modelling approach and (ii) a compact modelling approach.

The detailed modelling approach requires the resolution of every thermo-element in a TEC. Chen et al. presented a three-dimensional numerical study for a miniature TEC consisting of 8, 20 and 40 pairs of thermo-couples [5]. This study focussed on the influence of the scaling effect, and Thomson effect, on the cooling performance, and was later extended to transient analysis [7,17], the coupling of temperature and electric potential field [26], and a multi-stage TEC [25].

Instead of modelling each thermoelement individually, the second approach is to model the TEC module as a single bulk block, which is referred as 'compact thermal modelling'. This approach is more computationally efficient than the detailed modelling

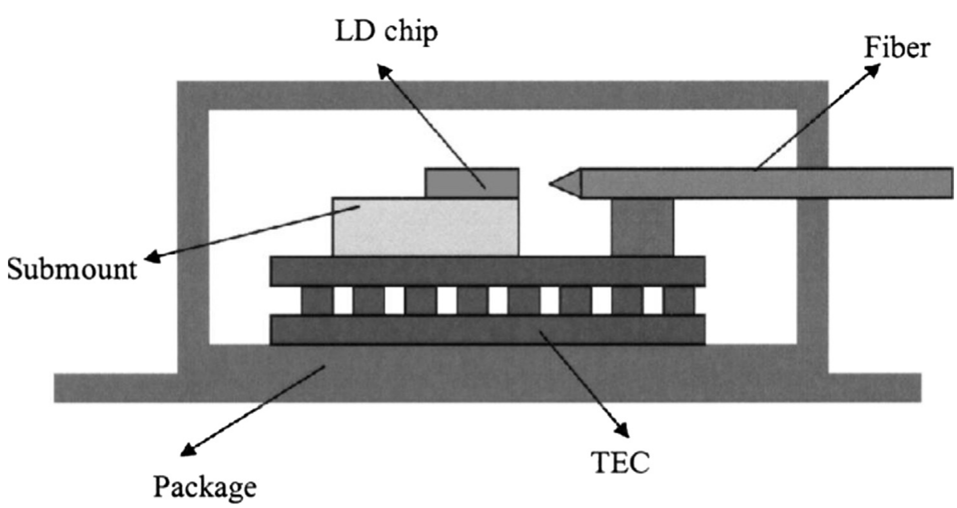

Fig. 1. Cross-sectional view of laser package [14].

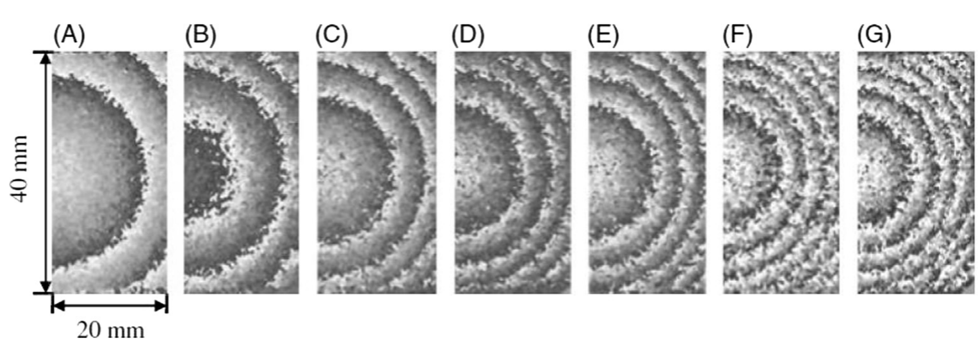

Fig. 2. 40 × 40 mm TEC wrapped phases fringe pattern under different current (0.06–0.18 A) captured by ESPI [3].