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PERFORMANCE OF A LINEAR, HIGH FLUX, FOIL AND SLOT THERMAL TRANSFER (FASTT) DEVICE

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1. ABSTRACT

The motion of thin foils through precision slots can provide high thermal flux cooling or heating at levels exceeding 3×10^6 Wm-2, over very wide operating temperature ranges from 100K to over 1000K. This paper examines the performance of a practical linear Foil And Slot Thermal Transfer (FASTT) device, both theoretically and experimentally. Previous theoretical models have assumed very low thermal conductivities for the construction of the foils. This assumption needs to be reconsidered when the material used for the foils exhibits substantial in-plane thermal conduction, such as with pyrolytic graphite sheet (PGS). A linear reciprocating foil device has been constructed and tested to examine cooling power versus foil speed. A simple lumped parameter theoretical model has also been developed to examine this performance parameter. The results from this model as well as those from the experimental device are presented, over the foil speed range from zero up to 0.06 [ms^{-1}]. The results from experiment and the simple theoretical model can be brought into good agreement by the addition of a simple thermal shunt resistance in the theoretical model. The reasoning behind this modelling adjustment is discussed, together with suggestions for further work.

2. INTRODUCTION

Foil And Slot Thermal Transfer (FASTT) devices offer a number of characteristics which are unique among heat exchange equipment. High thermal flux capability across a very broad range of operating temperatures, together with the use of non-hazardous materials, are of particular interest. These characteristics have received attention in earlier papers on FASTT Refs. 1, 2, 3 . Reference 4 examined the detailed construction and cooling flux capability of a linear form device. Cooling thermal fluxes, above 3×10^6 Wm^{-2} at temperature differences below 70CΔT were demonstrated. The same linear device has been used for the experimental portion of this paper. A direct comparison between the experimental performance of this device with a theoretical model will be given, as the reciprocating speed of the foils is varied from zero to 0.06 [ms^{-1}]. Theoretical modelling and experimental prototyping is part of a longer term development strategy to enable wider application of the technology.

The majority of heat exchange equipment utilises either gas or liquid convection as the primary means of heat transfer at its core. The logical extension would be to consider the use of the motion of solid media to facilitate heat transfer where this can potentially offer strong advantages in doing so. However, there is little evidence of practical devices being constructed to enable the demonstration of such advantages, particularly where high flux heat transfer is required. The motion of solid material as a heat transfer media involves a number of technical and scientific challenges, which presumably have deterred research into this area. The use of thin foils of solid materials, with their particular mix of physical characteristics, such as those used in FASTT devices, provides some insight into what may be possible. The combination of : very low thermal resistance, orthogonal to the direction of motion; low mechanical stiffness of the thin foils; density-specific heat products which can be greater than that of water; wide operating temperature ranges and low hazard/non-toxic materials, can add together to provide substantial benefits in some applications.

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Convective heat transfer, including two phase/boiling, forms the basis for much research work, and has been for many years. Fluids, be they gaseous or liquid, are essentially amorphous in nature which results in relatively poor levels of thermal conductivity (oils ~ 0.2 [$Wm^{-1}K^{-1}$] ; water ~ 0.5 [$Wm^{-1}K^{-1}$]). Exceptions to this are those materials which, although disordered, have high electrical conductivity, such as the liquid metals. Mercury and gallium both have thermal conductivities an order of magnitude greater than water (Hg ~ 9 [$Wm^{-1}K^{-1}$] and Ga ~ 35 [$Wm^{-1}K^{-1}$], but mercury is toxic and gallium has a propensity to form brittle intermetallic compounds with aluminium alloys, an undesirable characteristic in aerospace applications. The alkali metals such as lithium, sodium and potassium also have moderate to high thermal conductivities but their reactivity with many commonplace materials such as water and many metals makes these too hazardous to use in many applications and complicates recycling at equipment end of life.

The flow of fluids through pipes and channels produces a stagnation layer close to the walls of these transfer ducts as a direct consequence of their inherent viscosity and surface tension. This stationary layer can produce a significant thermal resistance between the main flow channel and the wall of the vessel through which the fluid is moving. This “boundary layer” may be reduced by forcing turbulence into the fluid flow, either by the use of turbulence generating structures, or through the shear forces generated in the boundary layer from radial velocity gradients. Unfortunately, both of these latter mechanisms result in pressure drops and increase the pumping power required to drive the fluid around the cooling circuit.

Two phase or boiling heat transfer can provide very high heat transfer coefficients and thus achieve appreciable thermal flux levels even with wall to liquid temperature differences below 10 C. One of the principle limitations to this form of heat transfer, is in the nature of the boiling phenomena. Liquid has to evolve into the gaseous phase and then be removed from the wall into the bulk liquid, while, at the same moment, fresh liquid is presented to the wall. Separation of liquid and gaseous phases can reduce flow disruption and can be provided by either wicks or channels for the case of heat pipes or by forced flow of liquid using nozzles/jets directed at the wall. Using such methods, heat transfer coefficients above 10^5 [$Wm^{-2}K^{-1}$] can be achieved at wall superheat temperatures of over 30CΔT and give rise to thermal flux levels above 3MWm^{-2} . The range of temperatures for which this flux level can be obtained is limited by the liquid used, with water providing an operating temperature range from 10C to above 150C. Liquids for other temperature ranges are generally far less capable in terms of flux levels due to lower thermal conductivities, higher viscosity and poorer specific heat capacity of these liquids.

Solid foils running in precision slots can provide “effective” heat transfer coefficients of greater than 30000 [$Wm^{-2}K^{-1}$] in helium, and with the capability of running with temperature differences of several hundred degrees. It is thus feasible to consider thermal cooling fluxes greater than 3MWm^{-2} using FASTT techniques, but over an operating temperature range from 0C to well over 1000C.

The core of any FASTT device utilising conduction as its primary thermal transfer mechanism offers the following :

Linear response relative to the temperature difference from source to foil, in terms of the thermal flux which can be handled. There are no sudden step changes in response to temperature differences.

High flux throughput above 200 Wcm-2 can be achieved with very low foil velocities of below 0.1ms-1 for devices in the 10 W to 10 kW power handling range.

The solids which can be used as the transfer media in FASTT can cover very wide operating temperature ranges, without recourse to cascaded systems.

2.1 Forms of FASTT

The rotary and linear forms of FASTT which have been described so far, are only part of a matrix of potential heat transfer devices which can be constructed using the basic foil and slot concept. The prototypes which have been produced to date, are of the OPEN form, where there is no requirement to seal the working zones from ambient air, and where air provides the conductive thermal connection between foil and core fins/slots. The use of air places performance limitations on a FASTT device, due to : the low thermal conductivity of air; the need to filter dust and other contaminants from the air; and, depending upon the operating temperature range, the need to consider relative humidity. Operation of unsealed devices below zero Celsius can lead to the build-up of ice on the moving parts. The ingress of dust through the motion of the foils through the slots can be a longer term problem with operation but relatively simple air filtration systems can eliminate this. The low thermal conductivity of air is something which is accepted within the design of a FASTT device operating in ambient air, and is catered for by design.

Essentially there are five major categories which form the “build” matrix which is possible with FASTT devices :

SEALING STATUS – SEALED OR UNSEALED

PREDOMINANT TRANSFER METHODS – CONDUCTION ; CONVECTION ; RADIATION

PREDOMINANT PURPOSE – COOLING OR HEATING

FLUX LEVELS AT SOURCE AND SINK - LOW, MEDIUM and HIGH. Thus it is possible to consider LOW to HIGH flux as well as HIGH to LOW flux thermal devices.

GEOMETRY – ROTARY OR LINEAR

The sealing status may depend upon the temperature range or on the performance flux levels expected, or other environmental considerations. Highest flux levels will be obtained in sealed devices with hydrogen or helium as the conductive media between foil and slot. Devices operating at sub-zero Celsius will generally be sealed to avoid ice build-up, if operating in humid ambient air.

The predominant transfer methods, within a device, can be

CONDUCTIVE : CONVECTIVE : RADIATIVE

And can be any combination of these depending upon the application. The existing prototype devices, built to explore FASTT, have been limited to CONDUCTIVE : CONVECTIVE types and have been UNSEALED.

The predominant purpose of the devices has thus far been for COOLING only. However, devices where the predominant purpose is heating are possible. Electrical heating may be more suited for many applications, but there will be those where the ability to switch rapidly from heating to cooling may be advantageous, such as in high intensity process temperature control.

The flux levels which can be catered for, using FASTT, cover the full range from low to extremely high. Very high input to output flux level ratios can be achieved by design. The approximately linear performance relative to temperature difference for these devices, allows very high flux levels to be maintained, if sufficient overall temperature difference, from source to sink can be provided. This characteristic contrasts with two phase heat transfer which can provide very high thermal flux levels, but generally over more limited operating temperature ranges.

3. EXPERIMENTAL

A linear form of FASTT device was chosen for the experimental prototype for this study. The device was unsealed and utilised ambient air for the convective portion. The device is comprised of a parallel array of foil strips which are attached to a reciprocating carriage. The foil strips are arranged to move in slots within a centrally placed "core" section. Thermal conduction provides the majority of heat transfer from the source, through the slot walls and thence through the narrow air gap to the foils. The thermally "loaded" foils exit the slots and enter the convectively cooled region where the passage of air ensures transfer of heat from the foils. The reciprocating motion allows the thermal charging and discharging of the foils to be continuous. The foils thus provide both the heat transfer media from the source/slots as well as the extended surfaces for convective dissipation to the air.

A slotted copper core forms the conductive portion providing a thermal path from the source to the foil, via multiple air gaps (slot walls to foils). The load is comprised of a conically machined copper block to which four 50ohm power resistors are attached. The resistors are based on aluminium nitride substrates and allow high flux levels to be achieved. The load block is attached to the core assembly using a low temperature tin, bismuth, silver, solder alloy (CHIPQUIK SMDLTFP). This jointing system provides a low thermal resistance interface. Pyrolitic graphite sheet was adhesively bonded to stainless steel foil to produce composite foils in the form of simple strips. Detailed construction and figures are shown in Ref. 4. A higher gear ratio than that used in Ref.4, was substituted to allow lower foil speed measurements to be taken reliably. A maximum foil speed of 0.06 ms-1 was set for both experiment and theoretical model. The "static" tests were conducted with equal lengths of the foil either side of the core. Power into the load resistor provided a well-defined measurable source which was monitored using voltage and current meters with accuracies better than 0.25%. The power into the linear reciprocating drive was monitored using an high accuracy voltmeter and an analogue, moving coil meter for current measurement. This latter meter, with reduced accuracy of only +/- 2.5%, was deemed suitable for measurement of drive power, providing a consistent, and simple method of smoothing in-cycle variations in power. The drive power usage is only a small fraction of the power needed for the fan which provides air motion through the foils. Typical power values are 0.6 W for the reciprocating drive and 6.0W for the fan at cooling levels of about 120W.

4. THEORETICAL

A simple thermal resistance/thermal capacitance model is the basis for the model. The thermal capacitance is alternately charged and discharged through two thermal resistances R_{in} and R_{out}. The input resistance is comprised of a series connection of thermal resistances from the source, through the base of the device and then through the slot sides (treated as fins) and then finally across the gap to the foil. A lumped thermal capacitance is assumed for the foil. A defined subsection of the foil length is then "exposed" to heating from the source through the resistances described above. The transit time is known from the speed of the foil, and the length of the core/slots. Likewise, the output, or convective section is defined by the transit time in this region. Exponential functions are used to describe the uptake and rejection of thermal energy within the cycle. The model is programmed in BASIC. Several cycles are executed to ensure that the temperature in the foil has reached the "settled" situation where there are steady maximum and minimum foil temperatures.

The pyrolytic graphite used as a major constituent of the composite foil, has very high thermal conductivity in-plane and is a simple way of expanding the area available for convective transfer. However, it results in non-zero heat loss at zero foil speed. This has been catered for, in the model, by the addition of a "shunt" thermal resistance. The shunt can also take into account air flow by-pass, and interfacial thermal resistances as well as "spreading" resistance at the root of the slots. Further work on each of these needs to be conducted to better understand device operation.

A separate investigation using finite element analysis was carried out to examine the effect of varying the exposed length of foil (outside of the core) on the performance of static air cooled devices. The heat transfer coefficient of the air was modelled at 40 , 60 and 80 $Wm^{-2}K^{-1}$, while the exposed length of the foils (length outside of the core) was modelled from 20mm to 100mm. Axial symmetry was used to reduce model size. An "equivalent" thermal conductivity approach was adopted to reduce element aspect ratios to below 10:1, for improved solution accuracy.

5. RESULTS

Figure 1 is a direct comparison of the experimental and theoretical work, with the use of a simple thermal shunt resistance in the model giving a good fit. However, a more detailed examination of the factors influencing the "shunt" resistance needs to be made as the results from the current finite element modelling are not in good agreement with experimental values of the static case.

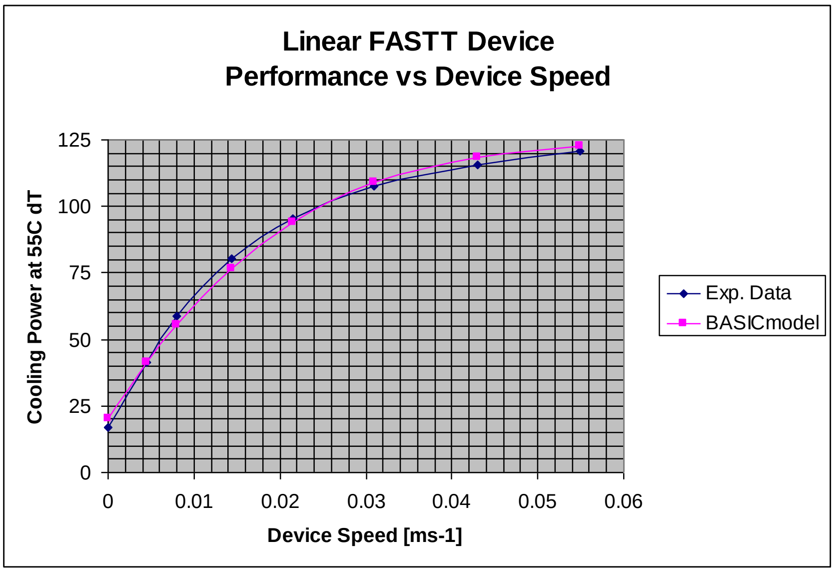

Figure 1 – Comparison between Experiment and the Theoretical Model

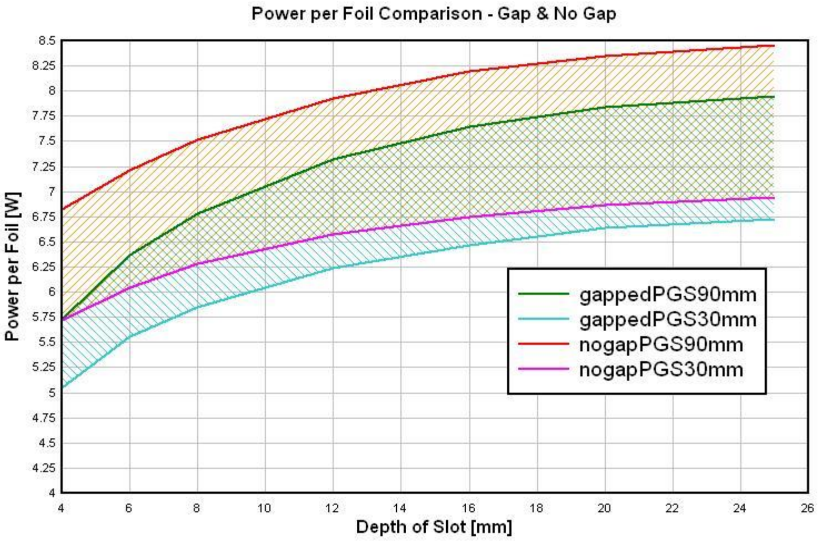

Figure 2 Cooling Power per Foil vs Slot Depth/Foil Width

Figure 2 compares the heat transfer resulting with an air gap being present between foil and slot against that resulting in the absence of any gap. The relatively minor difference in heat transfer due to the air gaps between foil and slot would be an encouraging factor in favour of FASTT devices, however, the finite element models predict much higher static values than experiment. There is evidently more work required in this area if future modelling is to support development of FASTT.

6. CONCLUSIONS

A simple lumped parameter, thermal resistance- thermal capacitance model of a linear foil in slot thermal transfer device has been produced, and the performance of such a device examined. Good agreement between model and experiment has been obtained by adding a simple thermal shunt resistance to the model. However, full justification for the use of the shunt requires further experimental work. A solid theoretical model of the FASTT thermal cycle is essential to assist in the design of future FASTT devices.

FASTT technology has a unique set of operating characteristics which continue to be developed, and which, hopefully, will contribute to expanding the portfolio of heat transfer solutions available to both industry and academia.

All thermodynamic machines, whether prime mover or heat pump/refrigeration types, rely upon efficient heat exchange. FASTT technology has the potential to expand the operating temperature range of these machines while ensuring compact high flux operation. Although the current work only considers single phase use of solids, the use of solid to solid phase transitions may open up new categories of machine.

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