Investigation on the Impact on Thermal Performances of New Pin and Fin Geometries Applied to Liquid Cooling of Power Electronics

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Abstract

Liquid cooling of coldplates and baseplates appears to be the near-term solution for the current cooling demand of the power electronics market. Although well-known manufacturing methods can produce adequate coldplates and baseplates for liquid cooling, new manufacturing processes and associated new geometries could significantly improve the hydrodynamic and thermal performances of current solutions. A numerical and experimental investigation has been carried out in order to evaluate the impact on the thermal performances of new pin and fin geometries applied to liquid cooling of power electronics. It is concluded that new geometries can provide a significant improvement on the thermal performances.

1. Introduction

Power electronics are used in many different applications from inverters in hybrid and electric vehicles, power conversion for wind and solar, traction drives for trains, to MRI amplifiers. Generally the higher power applications require liquid cooling of the power electronics. Since there are so many different applications with different requirements it is difficult to analyze all of the different cooling solutions. This paper will focus on hybrid and electric vehicle inverter cooling requirements. The heat fluxes, flow rates and other variables for hybrid and electric vehicle inverter cooling lend to the use of specific coldplate geometries. An important variable is the common need for a 1mm gap to protect against fouling or clogging of the coldplate. (Fig. 1) This 1mm gap requirement is a major driver of the coldplate geometry as well as choosing a manufacturing method for the coldplate. Both numerical and experiment methods have been devised to evaluate current coldplate geometries and manufacturing methods as well as new geometries and manufacturing methods. The goal of this study is to characterize the current and new geometries and optimize a geometry that provides the highest heat transfer coefficient per pressure drop and maintains a 1mm gap.

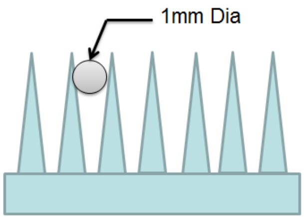


Fig 1. Typical automotive 1mm gap.

1.1. Brief introduction to power electronics used in inverter cooling of hybrid and electric vehicles

Most of today's hybrid electric vehicles (HEV) and electric vehicles (EV) have a liquid cooling system to keep the power electronics at a safe operating temperature. These power electronics, commonly insulated-gate bipolar transistors (IGBTs) are used in the inverter and converter parts of the electric motor drive. To put it simply; IGBTs are fast switching semiconductors that are about 98% efficient. Anytime there is a conversion of power; say DC batteries to an AC induction motor there is about a 2%

energy loss to heat in the IGBTs. When you consider a 75 kilowatt motor drive (~100hp) 1.5kw of waste heat is being generated.

This cooling loop is almost always a separate loop from the internal combustion engines (ICE) cooling loop. The main reason for this is that the common coolant temperature for an ICE cooling loop is ~105°C; this is too high for most power electronics configurations used today. Coolant temperatures for the power electronics are typically operating around 35-70°C with a max of 80°C. Most IGBT chips will begin to fail if die or junction temperature reaches 125°C or higher.

The most common form of power electronics is an IGBT module, which are manufactured by many companies worldwide. The IGBT module contains multiple IGBT chips soldered using a DBC or DBA process to a heat spreading baseplate (Fig. 2). The IGBT module will usually be mechanicaly mounted to an air or liquid cooled heatsink or coldplate, using some thermal interface material such as thermal grease.

The trend in commercial vehicle applications is to not use off the shelf IGBT modules but to use an integrated method. The main difference between an off the self IGBT module and using an integrated method is that there is no need for the use of a thermal interface material. Rather than mounting the module with an interface material to a coldplate with liquid flowing through it, the coolant is brought closer to the IGBT chips by flowing the coolant directly on the baseplate. This integrates the IGBT module and the coldplate, eliminating the thermal resistance of the TIM material and also some thickness of coldplate material. This will usually yield about 30% improvement in overall thermal resistance from coolant to junction. By doing this you are basically turning the baseplate of the module into a coldplate (Fig. 3).

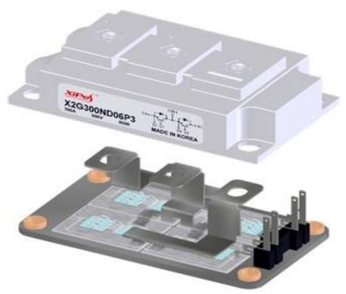


Fig 2. Typical IGBT

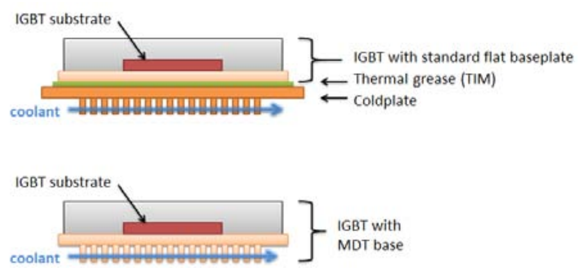


Fig 3. Typical and Integrated Baseplate Cooling Methods

1.2. Coldplate Geometries and Manufacturing Methods

Three different coldplate geometries will be characterized in this paper: straight fins, round staggered pin fins, and MDT in-line pin fins. All of these geometries meet the 1mm gap requirement. Height of coldplate geometry is held at 6mm and coldplate materials were kept the same so that geometry would be the only variable.

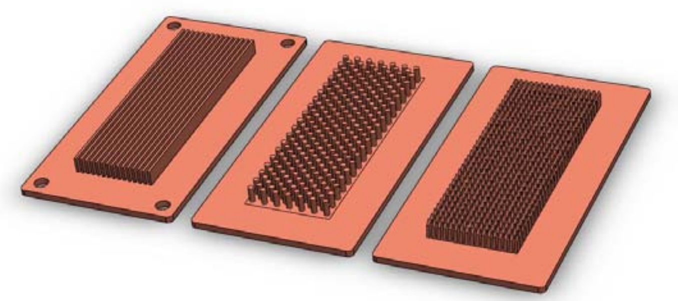


Fig 4. Three geometries tested: straight fin, round staggered pin fin, MDT in-line pin fin.

Typical manufacturing methods can be used to create the straight fin and round staggered pin fin such as machining or forging. The method used to create the MDT in-line pin fin is called micro deformation technology (MDT). MDT is a low cost, manufacturing method for creating fin and pin surfaces for use in heat transfer applications. This patented process employs a fixed tool, which mechanically and plastically deforms the work piece to form finite and repeatable fin and pin patterns. Unlike machining, EDM or etching this is not a subtractive process, and no metal is wasted. MDT Technology is highly flexible and can create a wide variety of fin, pin and micro-channel geometries.

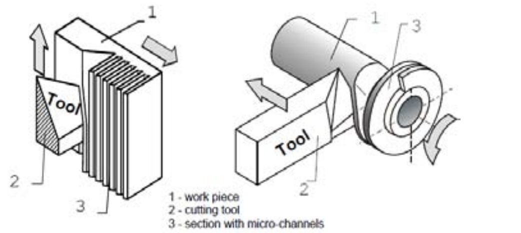


Fig 5. Micro Deformation Technology (MDT)

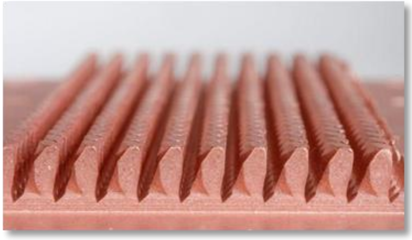


Fig 6. MDT In-Line Pin Fin.

2. Numerical and Experimental Method Descriptions

Both numerical and experimental methods where used to characterize and optimize the coldplate geometries used. Correlations between the two are provided in the results.

2.1. Numerical (CFD) Method Description

SolidWorks Flow simulation is used along with SolidWorks Design Study to help determine the best geometry given the input variables we are designing to. For all three geometries we are able to set upper and lower bounds for pin or fin height, thickness and diameter. For the MDT inline pin fin we can also optimize twist angle and cross cut.

SolidWorks Flow Simulation is based on advanced Computational Fluid Dynamics (CFD) techniques and allows you to analyze a wide range of complex problems. The software solves the governing equations using the finite volume method rather than the finite element method. A Cartesian adaptive mesh is used to capture the fluid, solid, and mixed volumes.

SolidWorks Flow Simulation solves the full Navier-Stokes Equations. The equations are supplemented by fluid state equations defining the nature of the fluid, and by empirical laws for dependency of viscosity and thermal conductivity on other flow parameters. Conservation equations are conserved; conservation of mass (continuity equation), Newton's second law of motion (momentum equation), the first law of thermodynamics (conservation of energy equation) and transport equations are used for turbulent kinetic energy and dissipation rate (k-e model).

The CFD model was based on the experimental test platform so that a correlation could be made between the two. Heat was added in the same area, and the inlet and outlet were modelled to match the exact specifications of the test platform. Temperature and pressure measurements were recorded at the same locations as the experimental test platform. The cooling fluid in both experimental and numerical is water at 20deg C. The power is 350 watts in a 90x32mm area in both the experimental and numerical tests.

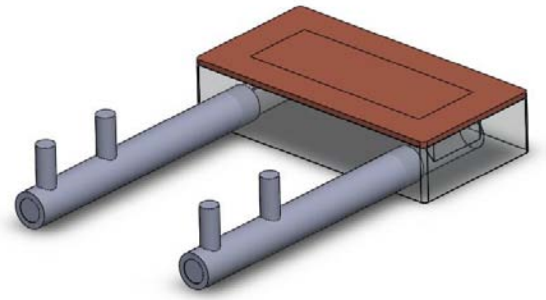


Fig 7. CFD model.

2.2. Experimental Method Description

An experimental test platform was built to test the different geometries with the same conditions as the CFD study. The setup consists of a test tub in which a test sample can be inserted. This test tub is connected to a temperature and flow controlled chiller. A custom heater which resembles the heat flux of a standard IGBT Module is applied to the test sample. This heater measures temperature, power and heat flux. Pressure drop is measured across the test sample using a differential pressure transducer. Temperature measurements are also taken at the fluid inlet, fluid outlet, and multiple locations on the test sample surface. (Fig. 7)

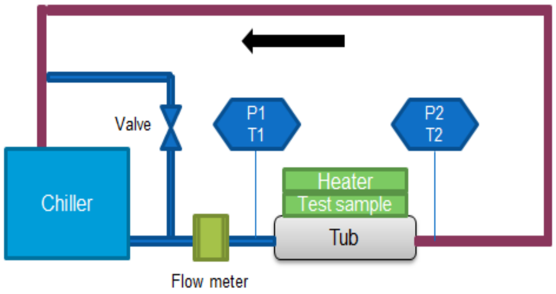


Fig 8. Experimental Test Platform Schematic.

Fig 9. Picture of experimental test platform.

3. Results: Characterization of Geometries

3.1. Numerical (CFD) Characterization of Geometries

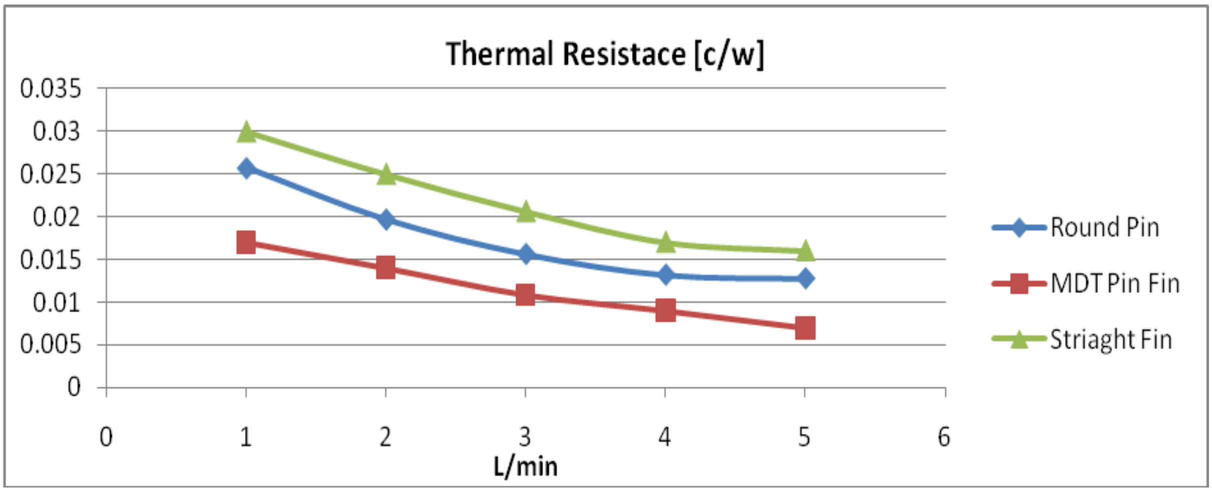
Numerical (CFD) data was collected on all three geometries.

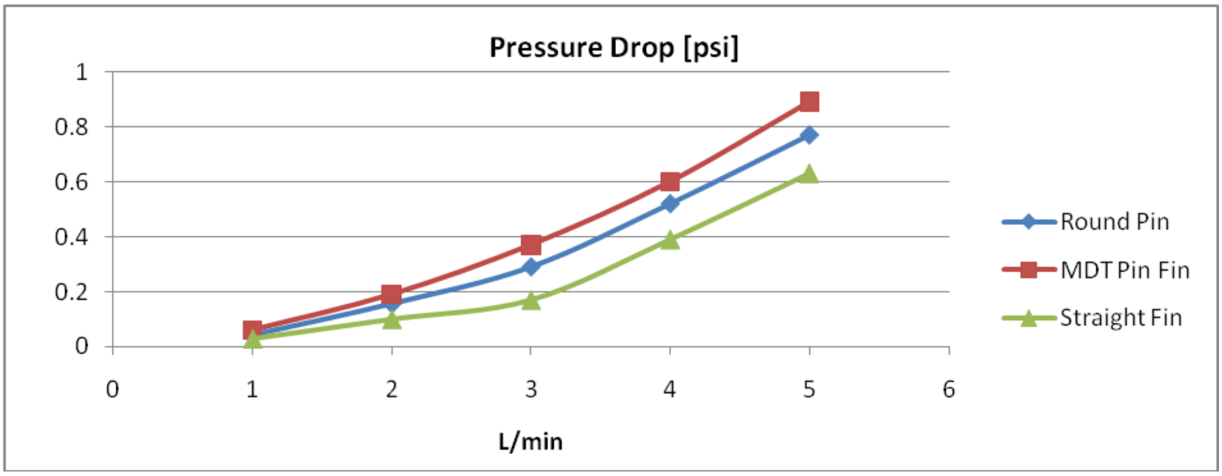
Tabulated Results:

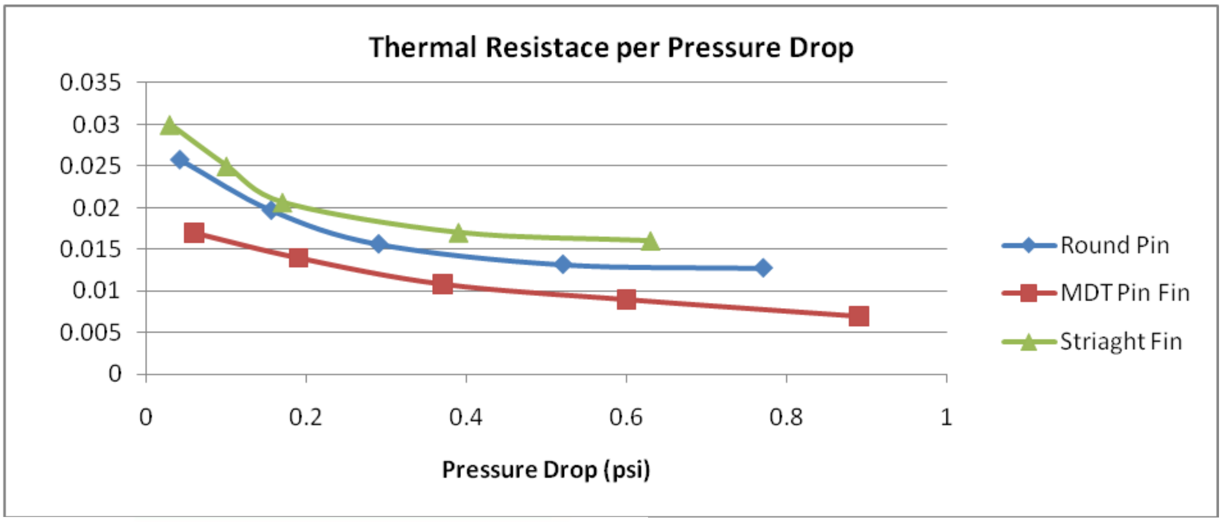
Straight Fin		
Flow (l/min)	Pressure (psi)	Thermal Resistance (c/w)
1	0.029	0.0321
2	0.101	0.0250
3	0.170	0.0206
4	0.390	0.0174
5	0.632	0.0161

Round Pin		
Flow (l/min)	Pressure (psi)	Resistance (c/w)
1	0.042	0.0257
2	0.156	0.0197
3	0.290	0.0156
4	0.521	0.0132
5	0.771	0.0128

MDT In-Line Pin Fin		
Flow (l/min)	Pressure (psi)	Thermal Resistance (c/w)
1	0.060	0.0171
2	0.190	0.0140
3	0.374	0.0109
4	0.612	0.0091
5	0.890	0.0073







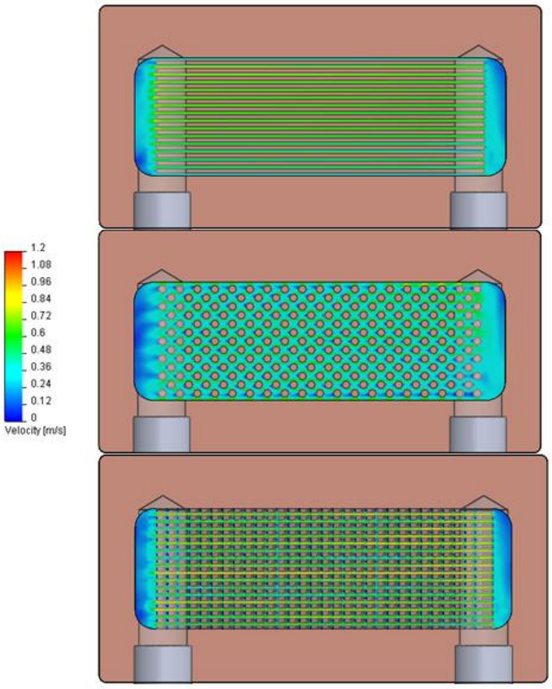


Fig 10. Velocity plots.

3.2. Experimental Characterization of Geometries

Experimental data was only collected on straight fin and MDT In-line pin fin.

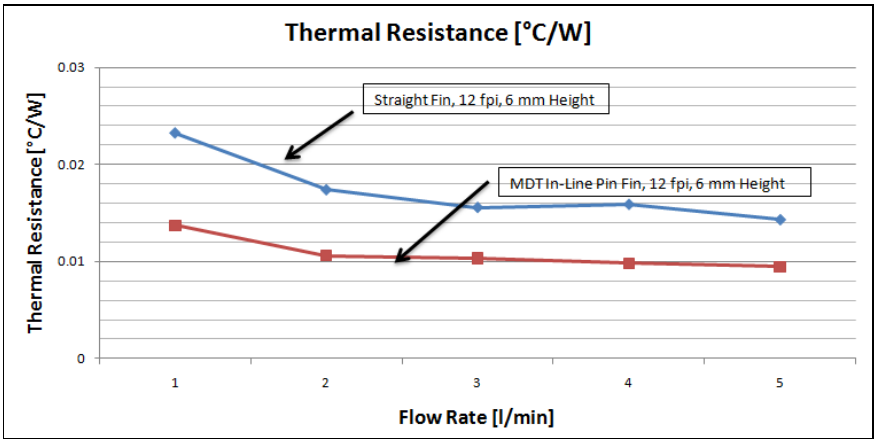
Tabulated Results:

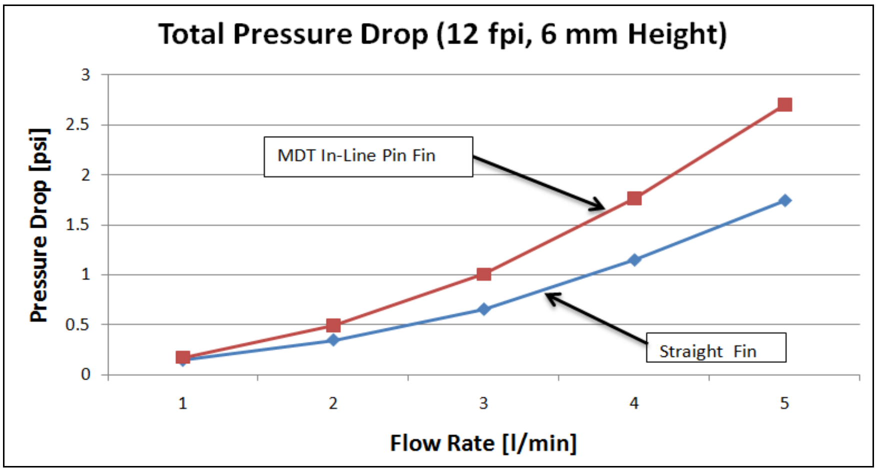
Straight Fin		
Flow (l/min)	Pressure (psi)	Thermal Resistance (c/w)
1	0.175	0.0232
2	0.497	0.0174
3	1.007	0.0156
4	1.765	0.0159
5	2.701	0.0143

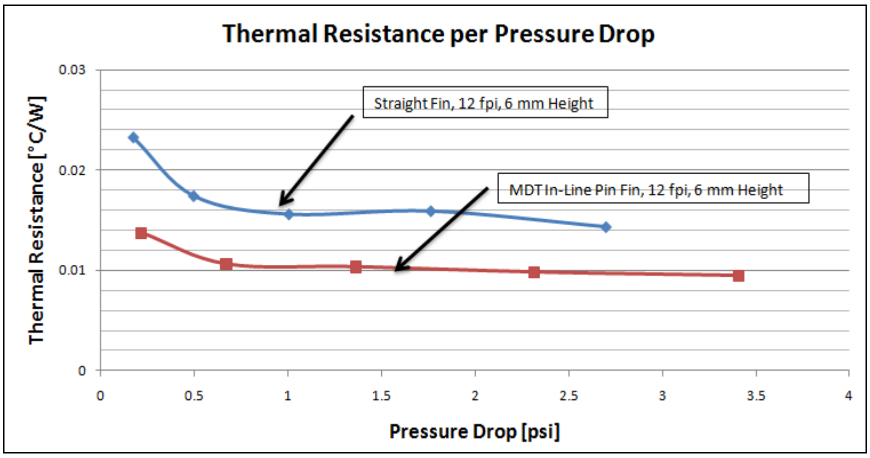
MDT In-Line Pin Fin		
Flow (l/min)	Pressure (psi)	Thermal Resistance (c/w)
1	0.219	0.0137
2	0.672	0.0106
3	1.365	0.0103
4	2.314	0.0098
5	3.409	0.0095

System Pressure Drop with no Fin or Pin Geometry	
Flow (l/min)	Pressure (psi)
1	0.128
2	0.264
3	0.569
4	0.997
5	1.527

*Pressure drop numbers shown are for the whole system including the fin and pin geometry, a test was run with no fin or pin geometry so we could subtract the system pressure to determine the pressure caused by just the fin or pin geometries.

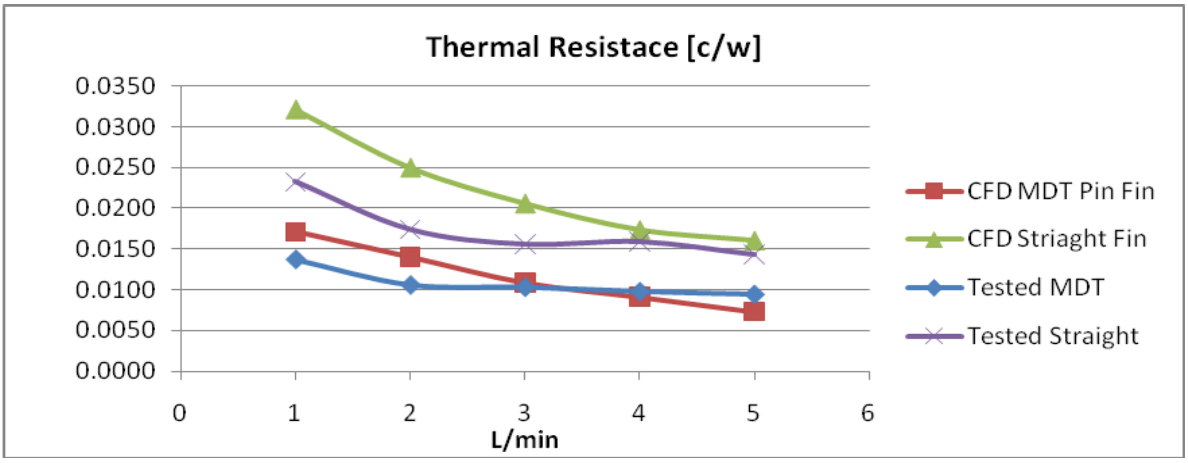






3.3. Correlation

Tested vs. numerical (CFD) results for thermal resistance:



Pressure drop was more difficult to correlate due to the complexity of the experimetal test platform.

4. Findings and Conclusion

MDT in-line pin fin has the best thermal performance per pressure drop when a 1mm flow gap is required at flow rates from 1-5 l/min. The twisted pin shape adds turbulence and breaks up of boundary layer increasing the heat transfer coefficient with only a minimal impact on pressure drop when compared to a straight fin or round pin fin.

5. Literature

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