BEER FRIDGE: A PERSONAL JOURNEY

ROBIN BORNOFF: “HOW FloTHERM HELPED ME DESIGN A COOLER MOUSETRAP”

WHITEPAPER

MECHANICAL ANALYSIS

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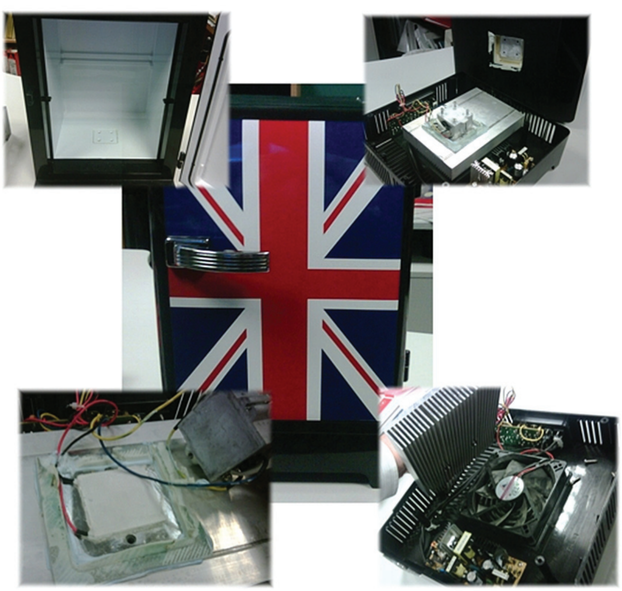
ABSTRACT

Mini-fridges, commonly filled with beer and the occasional moldering sandwich, have become a ubiquitous fixture in college dorm rooms and office break areas. But for some reason they never seem to cool their contents as well as their full-size cousins in the kitchen. This paper, based on a series of blog entries at http://www.mentor.com/blogs/tag/beer-eb5a0be6-a06b-4788-9b41-476b8c70454a, presents a light-hearted look at the problem and offers a solution. In doing so, it demonstrates some practical thermal analysis methods using Mentor Graphics FloTHERM™ and proves that thermal simulation can help engineers design better products for consumers.

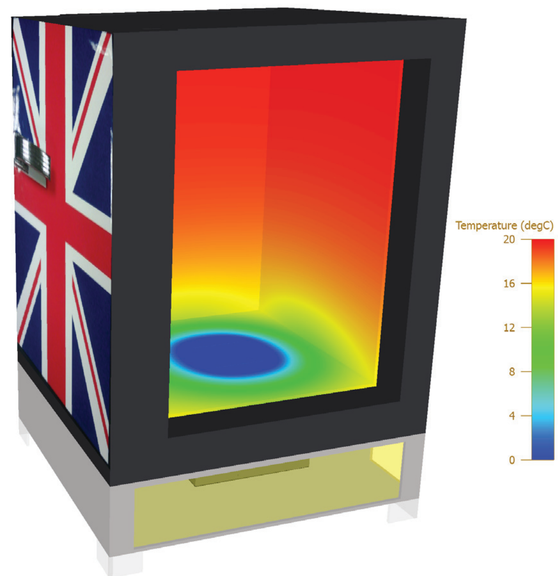
A GIFT

My boss, Roland, relocated from Germany to the UK a couple of years ago and has taken to life in England with alacrity. As a gift for the Mechanical Analysis Division's product development department (Hampton Court, UK) he bought a little fridge which has been busy ever since cooling the beer that everyone has been too polite to drink. A few weeks ago it stopped working. Some inquisitive minds and a couple of screwdrivers later it was in pieces with the conclusion that it was the thermoelectric cooler (TEC) that had given up the ghost. For a product whose raison d'etre is thermal I thought it would make a great case study in the application of FloTHERM for (retrospective) thermal design. In this white paper I will show how FloTHERM can be used to design a better beer fridge (the thermal equivalent of a better mouse trap?), taking time to showcase some of the classic FloTHERM features that ensure it remains the #1 CFD based tool used for electronics thermal analysis.

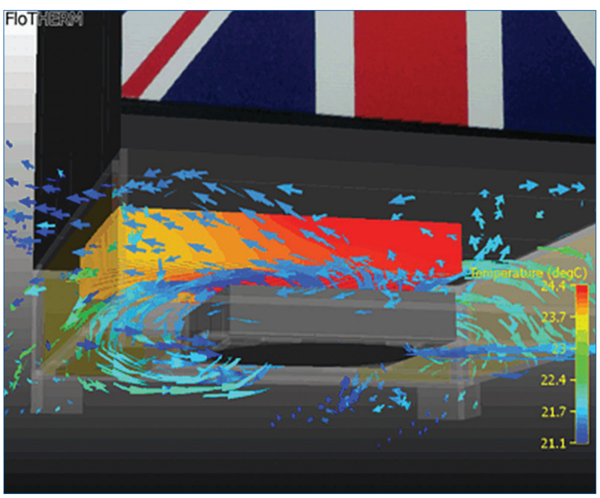
The fridge works by having a thermoelectric cooler (TEC) pump heat using the Peltier effect from inside the fridge down to a heatsink where a fan then blows cold air over it so that the heat is convected away from vents in the lower portion of the fridge housing. Such a flow of heat should ensure the space inside the fridge remains at a low controlled temperature. Much less noisy than the classic evaporator/condenser cycle approach used in most domestic fridge/freezers (though sometimes not as reliable!).



Such an application is considered a 'bread and butter' case for FloTHERM. Using nothing but a ruler I measured up the main constituent parts of the fridge and had created a 3D representation in FloTHERM in just over an hour. What took a little longer was obtaining the characteristic information for the TEC and the fan. Such objects are not modeled explicitly per se, a so called 'compact modeling methodology' is applied where their key physical behavior is retained but without modeling the exact physics of their operations. For the TEC, parameters such as the current required to pump a certain number of Watts against a temperature difference at two (hot side) temperatures are used as input to FloTHERM TEC 'SmartPart' object (this particular TEC was not a Marlow or Melcor TEC SmartParts available in the installed libraries). For the fan, the fan curve that relates the pressure drop over than fan to the amount of air that it can shift was required. Thanks to the beauty of Google (other search engines are available) such information was only a part number away.



The Union Jack was simply a matter of using FloTHERM's texture mapping capability, using a JPEG image taken by my phone camera. A 'fly-by' animation can be created by setting a few choice view points locations which are then traversed in sequence and output as an .avi (I used Corel™ to convert to an animated GIF). This, and all subsequent animation sequences, can be viewed in the original blog postings at http://blogs.mentor.com/robinbornoff/



Any competent user of simulation software should have at least a grounding in the theory behind the physics being simulated to the extent whereby the results generated can be perceived as either being realistic or not. Just a fancy way of saying that I expected the air within the fridge to be cold. Here are the surface temperatures on the inside of the fridge, with the side of the fridge hidden for clarity.

Not to cast aspersions on the purchasing power of my boss, but by all accounts this looks to be a real cheap and nasty fridge, not at all providing a uniformly cool interior. The TEC cools a little coldplate at the bottom of the inside of the fridge, sucking heat away from the air in the lower portion of the fridge but, as hot air rises, the cold air simply stays at the bottom.

In terms of the effectiveness of the fan, a good design would have the fan induce cool air from around the underside of the fridge, blow it onto the heatsink, the air would heat up, then the vents should be arranged so that this warmed air vents back into the room. One thing you wouldn't want is for the warm air to re-circulate back into the underside intake of the fan to be blown back into the heatsink. Oh dear….

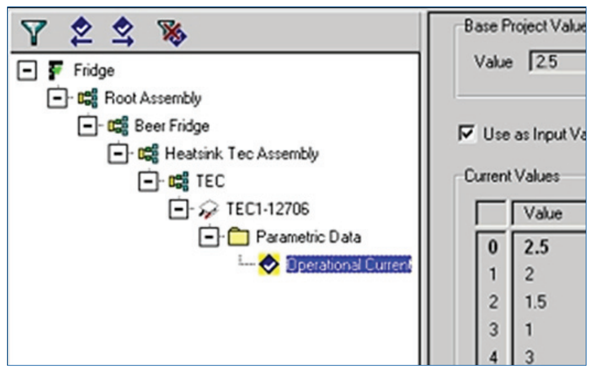
Going back to the TEC, one thing I did have to assume was at what current it was set to operate at. For this model I guessed at 2.5A. TEC performance is very sensitive to this, I wonder what an optimal TEC operating current would be for this fridge...

TEC EFFECT

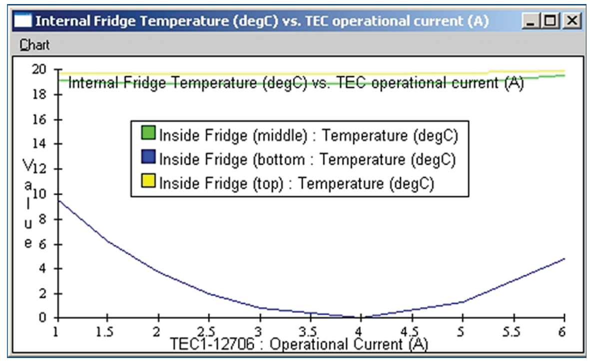
Beer drinkers are notoriously quiet people and as such would not want to be disturbed by the continuous hissing and whirring of a classic compression/expansion refrigeration cycle type beer fridge. They would argue that's why both kids and kitchens were invented. Kitchens to put the noisy fridge in, kids to go get the next beer. Electric coolers, fridges that utilize thermoelectric coolers (TECs) to pump the heat from inside the fridge thus keeping it cool, should therefore be more widespread as they are notoriously quiet(er). Unfortunately they are also about 6 times less efficient, requiring much more power to keep the fridge at what is known in the trade (the beer drinking trade) at beerdegreesC. But if you're just trying to cool a small space that doesn't require that much cooling work then what's a factor of 6 amongst friends. A TEC based fridge is much more portable than its hissing shuddering bigger brother. Why, you could even plug such a small fridge into a car cigarette lighter to cool your beer for the long journey (!?).

A TEC works by having an electrical current passed through a chain of semiconductor PN pairs that result in an imposed temperature difference between the two ceramic sandwiched 'sides' of TEC which thus results in a net flow of heat that is pumped through it. It's like the conductive equivalent of an air moving fan that takes electrical power, spins a motor with blades on it which then induces air flow through it. For a TEC if you supply too little operational current it doesn't pump enough heat, if you supply too much then its pumping performance degrades due to the increased Joule (self) heating that occurs within it. (At least that's how I visualize these novel little chaps, am sure a TEC expert would correct me on one or more of the points above…).

Let's use FloTHERM, the #1 CFD based electronics cooling simulation tool, to investigate the relationship between the TEC's operational current and the resulting air temperature distribution within the fridge. FloTHERM has an application window called the Command Center. This window allows for just about any parameter of a FloTHERM model to be varied and for the results of the subsequent scenario of variations to be presented back to the user. In this case I'm going to vary the TEC operational current between 1 and 6 Amps. Here's what that set-up looks like in the software:

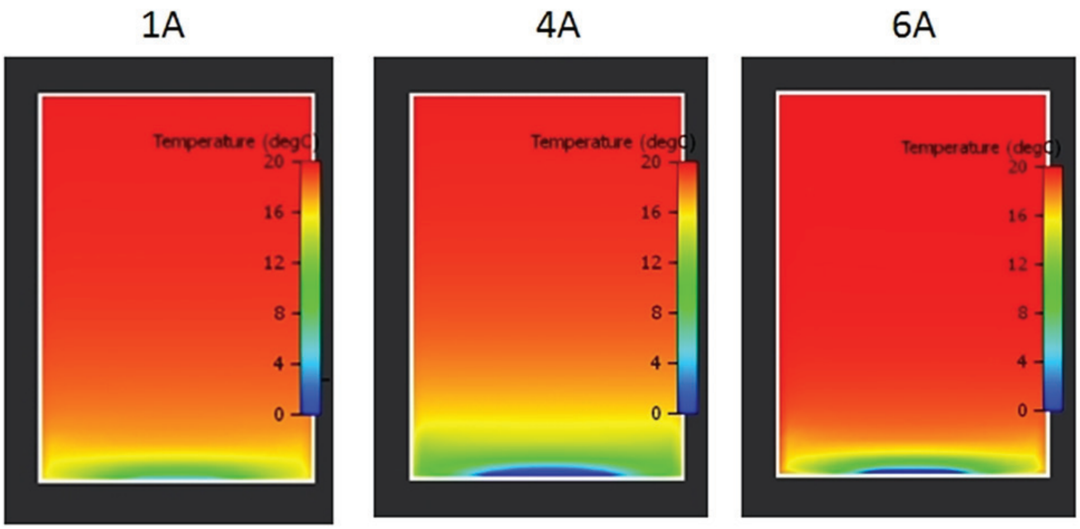


One click of the GO button will have FloTHERM solve all these variants and present the results back. One of the simplest ways to inspect the results is to note 'monitor point' temperatures, temperatures at defined points in the model, in this case inside the fridge right at the bottom, in the middle and at the top:



(OK, agreed, not the most visually compelling of graph styles, like many other CAE vendors we realized a long time ago not to attempt to compete with the graphing style and formatting power of Excel, better to focus on the export of simulation data to it).

At about 4 Amps the TEC performs best, the temperature at the bottom of the fridge is lowest. Currents below or above that result in a degradation of performance. Interesting that the middle and top of the fridge are always warm, too warm. Let's dive down and look at the temperature distributions for the two extremes and the optimal points:



Due to our friend 'stable stratification' even the colder air at 4A at the bottom of the fridge is just sitting there. There is no way for the cold to reach up to the top of the fridge. So in all cases the top of the fridge remains too warm (unless you're a real ale drinker).

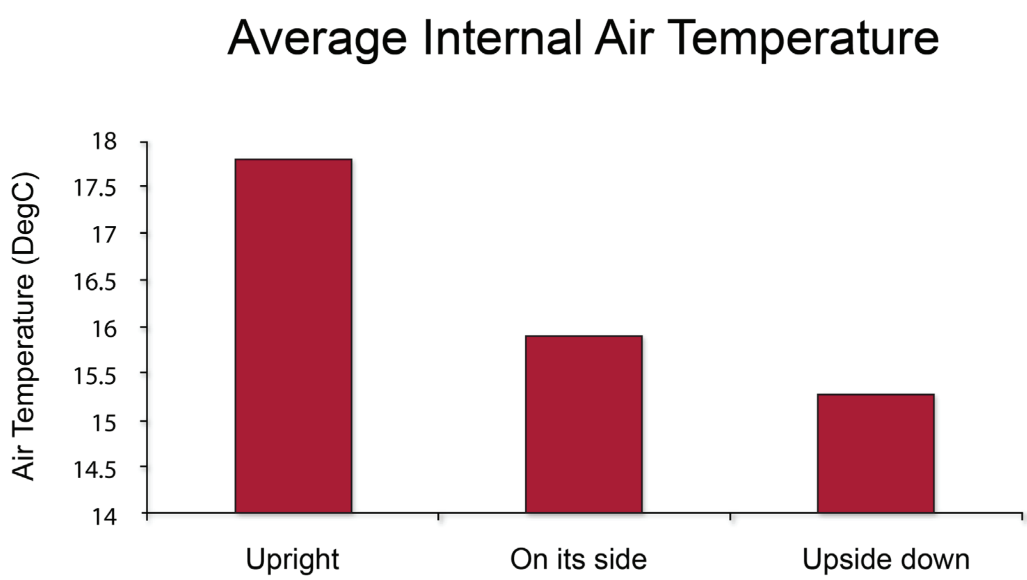
So, how would you get the cold to better spread around the inside of the fridge? How about stocking it full of beer so that the cold can conduct up through it all, or maybe turn the fridge upside down to get the cool air to dump down and spin the air inside the fridge around?

SIDE UP OR UPSIDE DOWN?

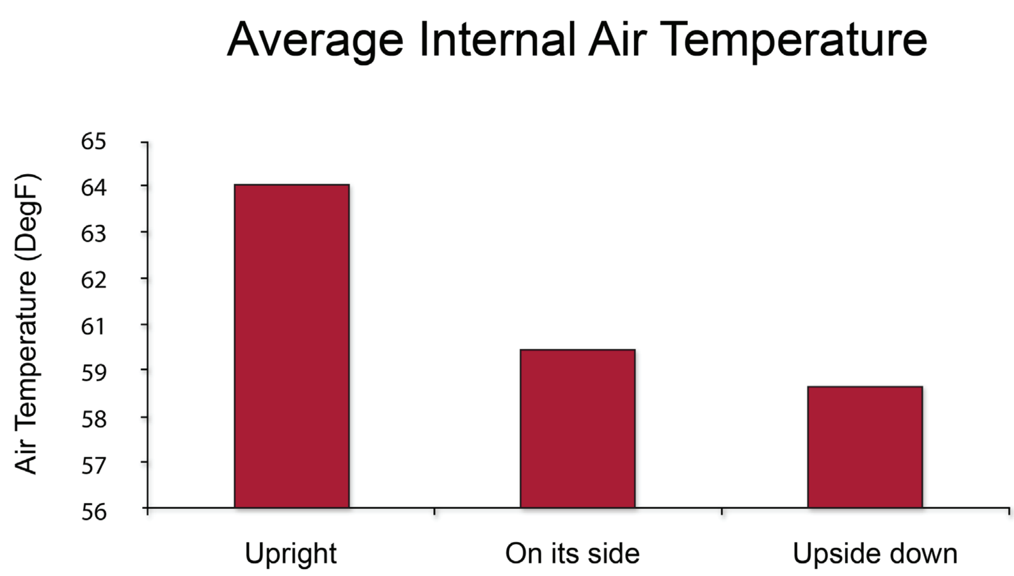
The futility of investigating the cooling effectiveness of any empty fridge is beginning to dawn on me, the irony of which is matched only by my new-years-resolution-inspired-sobriety. Never mind, let's see this particular study through… Whether in a beer ridden fury or in moments of Galilean scientific investigation, you might find yourself kicking the fridge over on to its side or even lifting it up and plonking it upside down. The door is tightly closed so why would the potential beercoolingosity in any way be affected? Let's find out.

As shown previously, the TEC only cools a small metal plate on the bottom face of the inside of the fridge. Air next to the plate is going to be the coldest inside the fridge, getting warmer the further away from the plate it gets. Even the most ardent non-engineer should know that 'hot air rises' (and 'heatsinks' but that's another story…). With the fridge upright and the cold plate on the bottom of the inside of the fridge the cold air just sits at the bottom with the warmer air stagnating above it. Once the fridge is on its side or upside down the air cooled by the plate dumps down to the bottom of the fridge mixing things up inside.

The main effect of this is to reduce the average air temperature. After a couple of assembly rotations and subsequent simulations conducted in FloTHERM, the following chart shows the effect of the rotations.

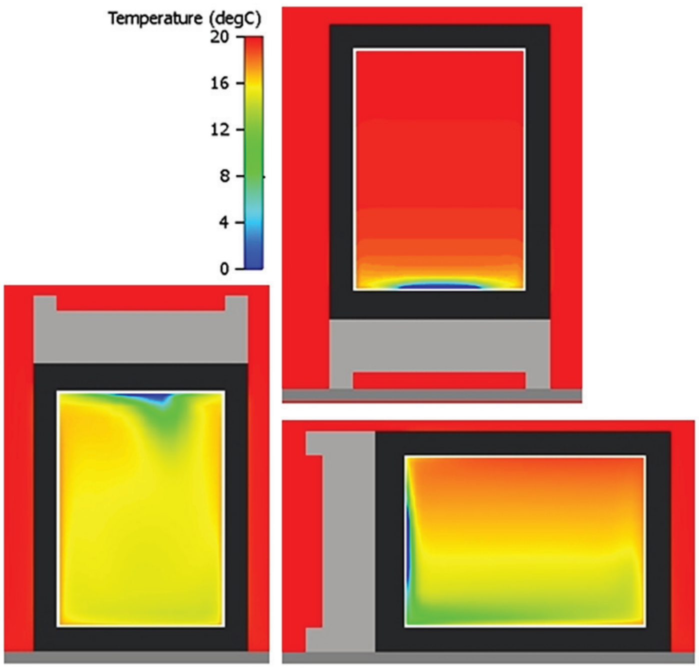


If you hail from the US, Burma or Liberia and thus do not officially use or mandate a metric system of units then you'd be more familiar with:

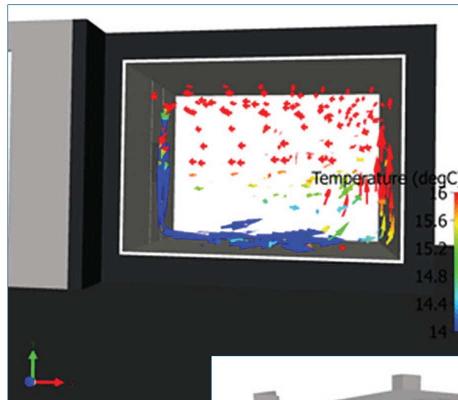


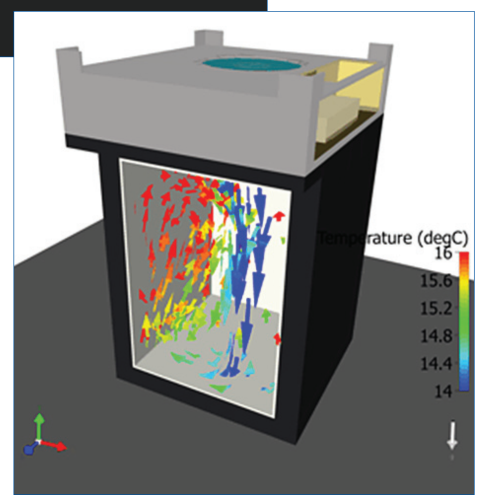
Either way, an empty electronic fridge sure doesn't get that cold.

In a little more detail, here are the temperature variations within the fridge, as predicted by FloTHERM:



The mixing effects of the cold dumping air can be seen when you start to animate the airflow inside the fridge (note I've reduced the temperature range to go from 14 to 16 degC, blue is =<14, red is => 16 to clearly show the hot air (rising) and the cold air (sinking), note that the speeds are not to 'scale'):





Think about the inverse of the problem; even my dog would intuitively know that putting a radiator on the ceiling would not be the best way to heat a room. There is more to product design than just thermal however. Simplicity leading to a reduction in manufacturing costs is going to be a biggie. The structural instability of having the heatsink, fan etc. on the top would maybe increase the risk of litigation. The point is that such small fridges are not designed to be empty. Stock it full of beer cans and you might think it would not get as cold everywhere. You might have to think again…

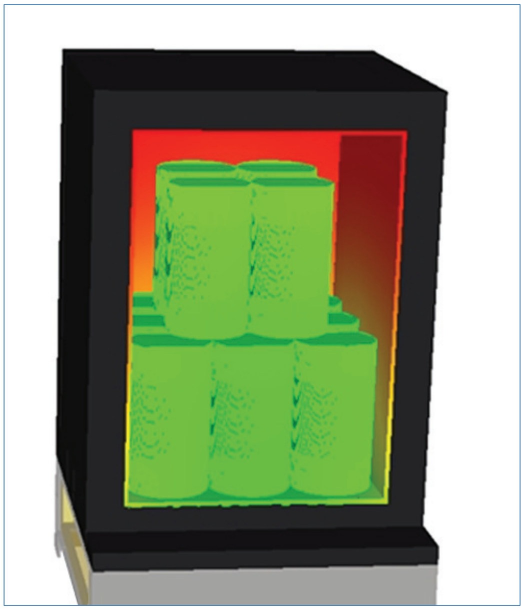
FloBEER

As the ancient proverb goes; a beer fridge without beer is like X Factor, utterly pointless. You'd have thought that by clogging up the insides of the fridge with pesky cans of beer you'd cripple its thermal performance. As someone once said of Simon Cowell …"O, how wrong you are".

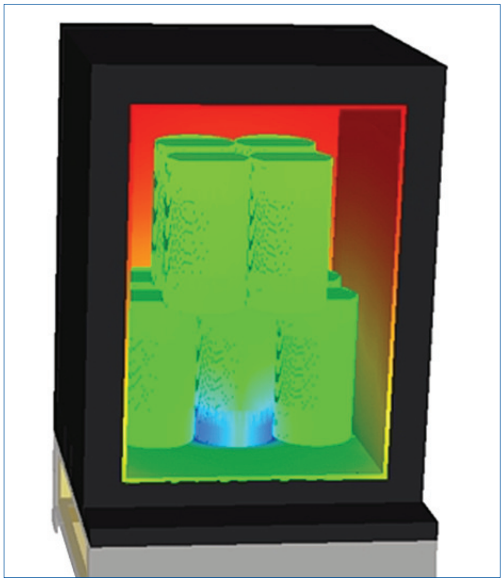
When modeling a can of beer in FloTHERM, in fact when modeling any part or object, you have some options when it comes to how to represent it. Would you worry about including a definition of the printing on the side of the can? No, even my pet cat would realize that what's shown on the side of the can would have no effect on its thermal behavior. Would you explicitly model the inside of liquid inside the can? In theory yes you could but let's be a bit pragmatic. As already covered, when the fridge is upright the temperature variation inside the fridge is such that everything is quite stable, cold on the bottom, hot at the top, stably stratified. The same is going to be true of the temperature variation within each can, the result being that the liquid inside is just going to sit there, more like a solid than a liquid, and somewhat easier to simulate. So, let's model each can as a solid cylinder with a thermal conductivity representative of the (stationary) liquid surrounded by a thin sheet of metal. With little thought and less attention I came up with a value of 5 W/mK.

Texture mapping is a neat feature of FloTHERM's post processing window, the Visual Editor (and it's free and freely available stand alone counterpart, FloVIZ). It's quite straight forward to create this image and map it to the FloTHERM cylinder object and hey presto, you have a can of FloBEER! The picture is of Hampton Court, seat of the great kings of England most notoriously Henry VIII and just down the road from the office…

Let's stock 13 of these cans in the fridge, close the door and see what happens…



Compared to the average temperature of about 18 degC when the fridge was empty, the average temp when the beer's in the fridge has gone down to 13.6 degC with the average temperature of the beer itself down at 10.1 degC. Not all cans are equal, not surprisingly the can sitting on top of the cold plate is coldest (shown here by hiding the 3 cans at the front):



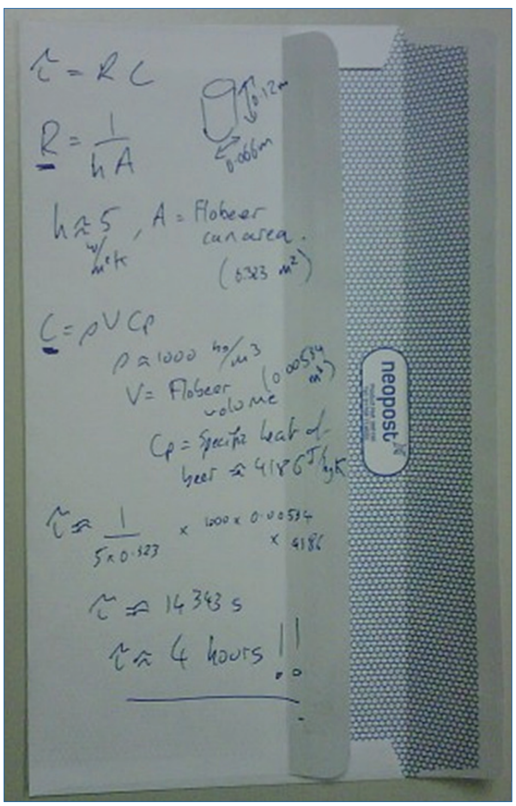
Getting the cold to conduct up into and spread through the cans is a far more effective method of getting the cold from the TEC up, into and around the fridge. Even moving air is no match for the conductive ability of the FloBEER.

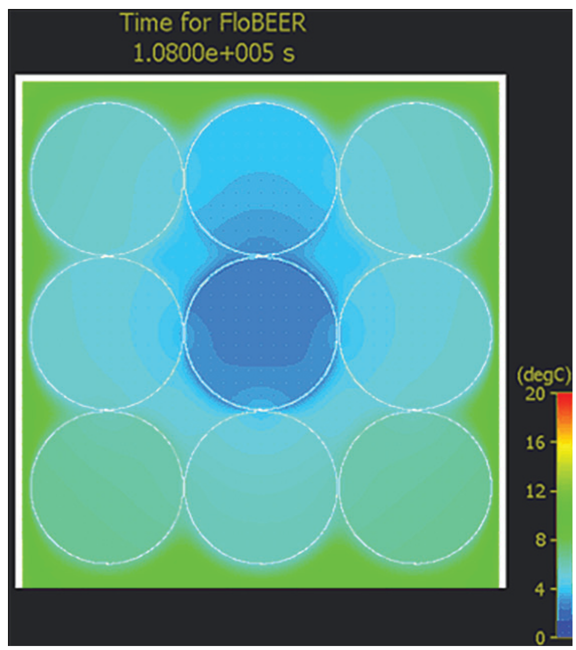
TIME FOR A FloBEER

All good things come to those who wait. For beer this entails a trade off between anticipation and satisfaction. If, too soon after you put the room temperature beer in the fridge, you get your child to grab a beer for you, your thirst might be quenched but your satisfaction might not be. Wait too long for it to cool down and you might forget you wanted one, or go to sleep, or hit the whisky instead. A transient thermal simulation will tell you how long, and how evenly, the beer cools down…

A time constant is a resistance multiplied by a capacitance. Maybe the combination of a resistance to refuse a free beer x your capacity to drink many. A back of the envelope estimation as to how long it would take warm beer, placed in a cold environment, to achieve its cool temperature can be made. Thermal resistance = 1/heat transfer coefficient x area, a thermal capacitance = density x volume x specific heat, a time constant = thermal resistance x thermal capacitance. The time constant will be the time it takes for the beer to cool down to about 2/3 of the way to minimum. And here's the envelope…

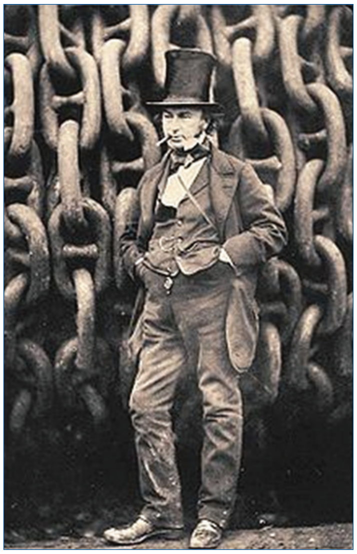
When doing a transient simulation in FloTHERM one has to define for how long you wish to predict the behavior of the system. Using the back of the envelope calculations helps set an initial guess for this duration. The rest is simply a matter of waiting for FloTHERM to crunch through the simulating. The end product is a series of predictions of the full 3D temperature distribution at many points in time (time steps). This information can be animated to show the how the cold penetrates the cans.





There's a bit of a cold bias towards the rear of the fridge, away from the door so either the bottom middle or bottom rear beer would be the best to grab first. Remember to move the remaining cans to fill the hole you've just left and turn either to the envelope or FloTHERM if you want to estimate or simulate (respectively) how long you should take to drink the current one until the next one has cooled further down to acceptable levels.

BAFFLES AND BOTTLENECKS

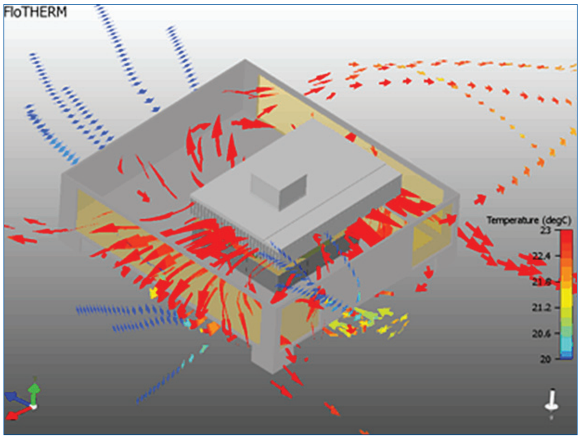


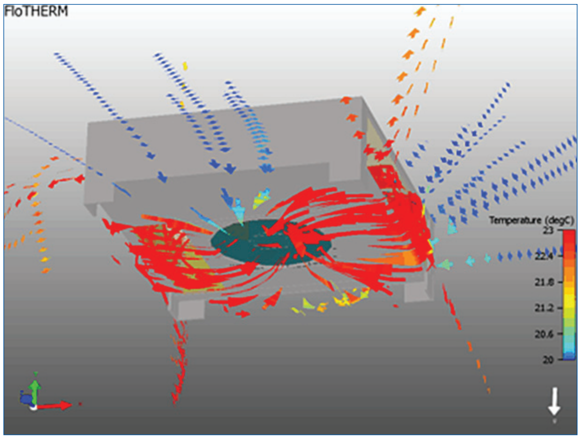
For a white paper focused on thermal design there has been precious little design presented so far. Design is the process of making a plan for the construction of an object/product. Whether you subscribe to the rational or action-centric model of the design process, some form of iteration and adaption is used to arrive at a design that is fit for production. Trying an idea, seeing it fail, finding out why and trying a better idea next is the essence of design success.

The British Empire was fuelled by the engineers that drove the industrial revolution and who reaped the benefits of the resulting products. Engineering entrepreneurship in the 19th century saw success and failure stand together. Brunel's choice of broad gauge railway when chief engineer of the Great Western Railway and his use of atmospheric (vacuum) traction on part of the GWR line were both fated. The attitude of 'nothing ventured, nothing gained' and 'you don't learn anything by getting it right first time' seem to have been designed out of today's profit-ridden society.

With that in mind let's get back to the fridge. Testing a physical prototype with some smoke flow visualization, prior to a commitment to manufacture, would have brought to light the fact that the venting arrangement and configuration of the fan and heatsink are far from optimal. The TEC works well if the heat that it sucks out of the fridge is effectively removed from the system by passing that heat to the heatsink and for the fan to blow cool air over the heatsink with the resulting hot air evacuated to the room. The room would then warm up (a little) leading you to desire a beer to quench your thirst. A nice symbiotic symmetry. It's always better to make your mistakes before something goes to market.

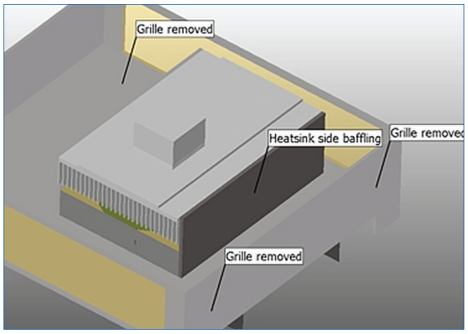
> " A life spent making mistakes is not only more honorable, but more useful than a life spent doing nothing. "
>
> George Bernard Shaw

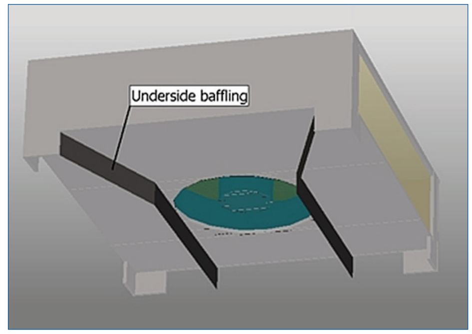




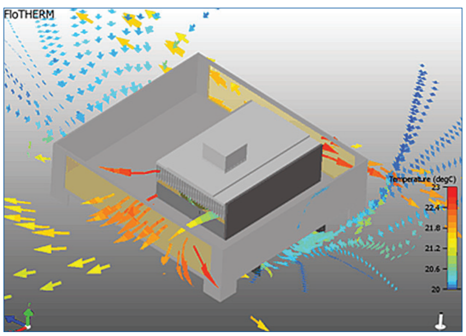
The resulting flow fields of the FloTHERM simulation shown above, with the moving air arrows coloured by temperature (red is hot) and the fridge enclosure itself hidden for clarity, clearly show that the hot air issuing from the heatsink is being sucked back down under the unit and back into the fan. Far from nice cool air being blown on to the heatsink it's actually heating itself (well, not being cooled as much to be precise). In addition, some of the air blown onto the heatsink does not move down the extruded fin channels as it should, instead it smacks into the fins and promptly decides to go sideways through the gap between the heatsink and the fan, wasted air.

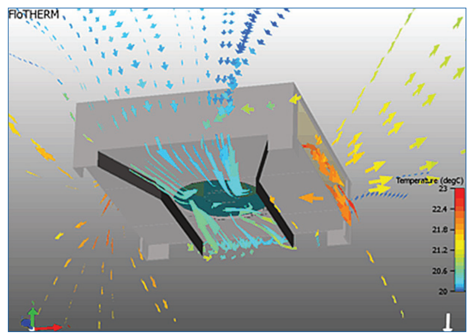
Having identified these deficiencies we can propose a design alteration. Let's use baffling to ensure that only cool room air gets sucked into the fan, the fan pushes air through the heatsink fins channels and the resulting hot air leaves the system, never to be re-ingested:





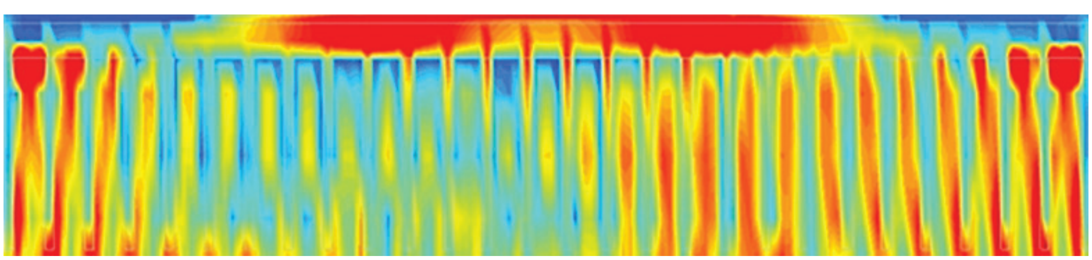
(Colin Chapman eat your ground effect heart out). For a little bit of extra plastic, the effects are quite good:



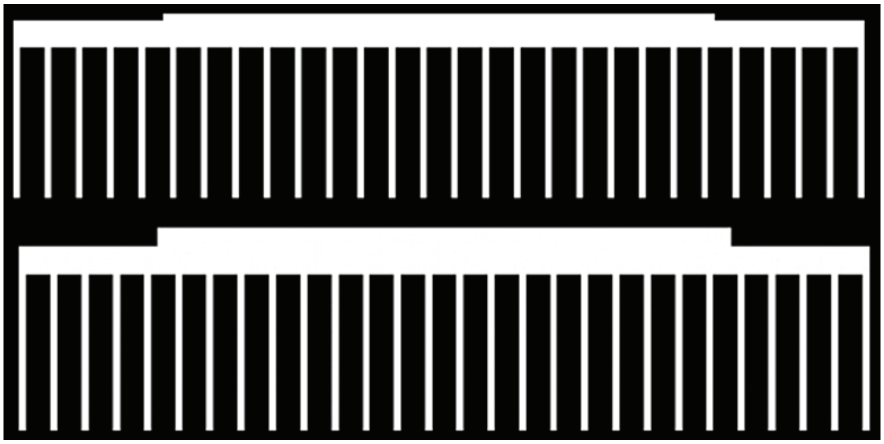


Now that the air flow is better managed let's turn our attention to the heatsink itself. Heatsinks don't magically sink the heat out of existence, they are, to use a better phrase, area extenders. For the price of a (very) little more solid thermal resistance in the form of more aluminum, the heat can be passed to the air over a much larger surface area resulting in more effective cooling. Heatsink design is a science in itself. Number of fins, fin thickness, fin spacing, heatsink length etc. are all interrelated parameters. Let's keep it simple and just look at the heatsink base thickness.

In the current release of FloTHERM, V9, we introduced a novel (and patent pending) capability to visualize where thermal bottlenecks exist in a design. From a heat-sinking perspective a good design is one where the bottlenecks are as uniform as possible, i.e. heat finds it equally easy to pass through all parts of the metal on its way to the air. Looking at the distribution of BN on a plane through the heatsink we can see where it builds up in the central portion of the heatsink base:



To relieve a bottleneck you could use a material with a higher thermal conductivity, or make the cross sectional area the heat passes through, larger. The latter is much cheaper, let's increase the base thickness in the middle portion some more:



All well and good but how would we determine the effectiveness of the baffling and heatsink design modifications? Well, if the system is working more efficiently then surely the TEC would require less power to maintain the fridge at the same temperature as before. In my opinion this is a better metric than just making the fridge colder, any colder and the beer would start to freeze! With the above two changes the TEC requires only 3.2A (down from 4A) and pulls 23W (down from 37W). If you're wondering, the difference in the ratios of current reduction and consumed power reduction will be down to temperature dependent self heating effects in the TEC, all handled automatically bz FloTHERM.

FloTHERM + Beer Fridge Design = 35% energy savings

CONCLUSION

A 35% energy savings, not to mention generally better cool air circulation, transforms a commodity product into an appliance with unique advantages for the beer-consuming public. While most individual beer fridge owners lack the tools to do a proper thermal analysis (though FloTHERM is openly available from Mentor Graphics…), the foregoing highly scientific investigation points toward an opportunity for mini-fridge manufacturers: even a cursory thermal simulation can help improve their products' value and competitiveness.

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