A Self-Contained System for Thermal Management of Next Generation High Heat Flux Electronics

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Outline

- Background
- Objectives
- Micro-structured surfaces
- Description of force-fed technology
- Evaporator: experimental setup and results
- Condenser: experimental setup and results
- Conclusions

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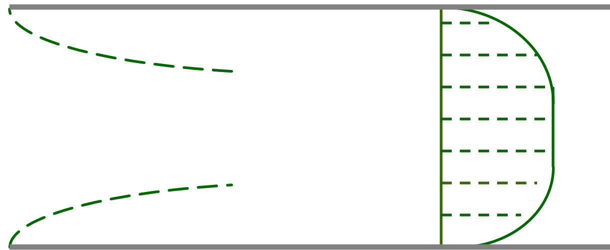
Heat Transfer in Channels



Developing

Fully-Developed

- Primitive Variables - Fully Developed

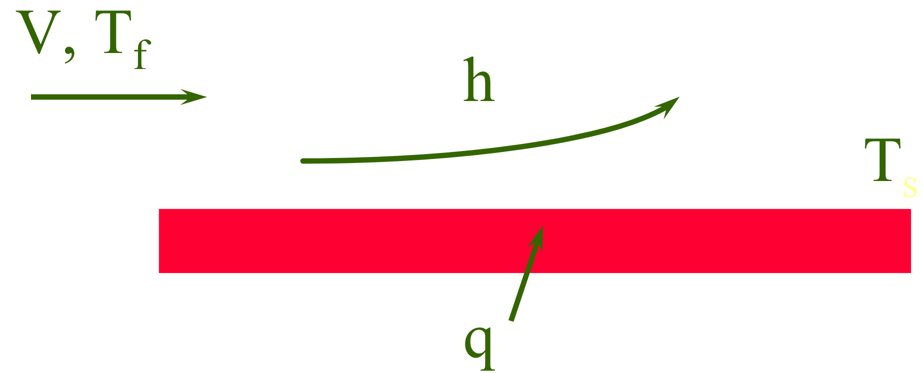
  h = f (Fluid, Diameter, Temp..)

- Primitive Variables - Developing

  h = f (Fluid, Velocity, Distance, Temp. .)

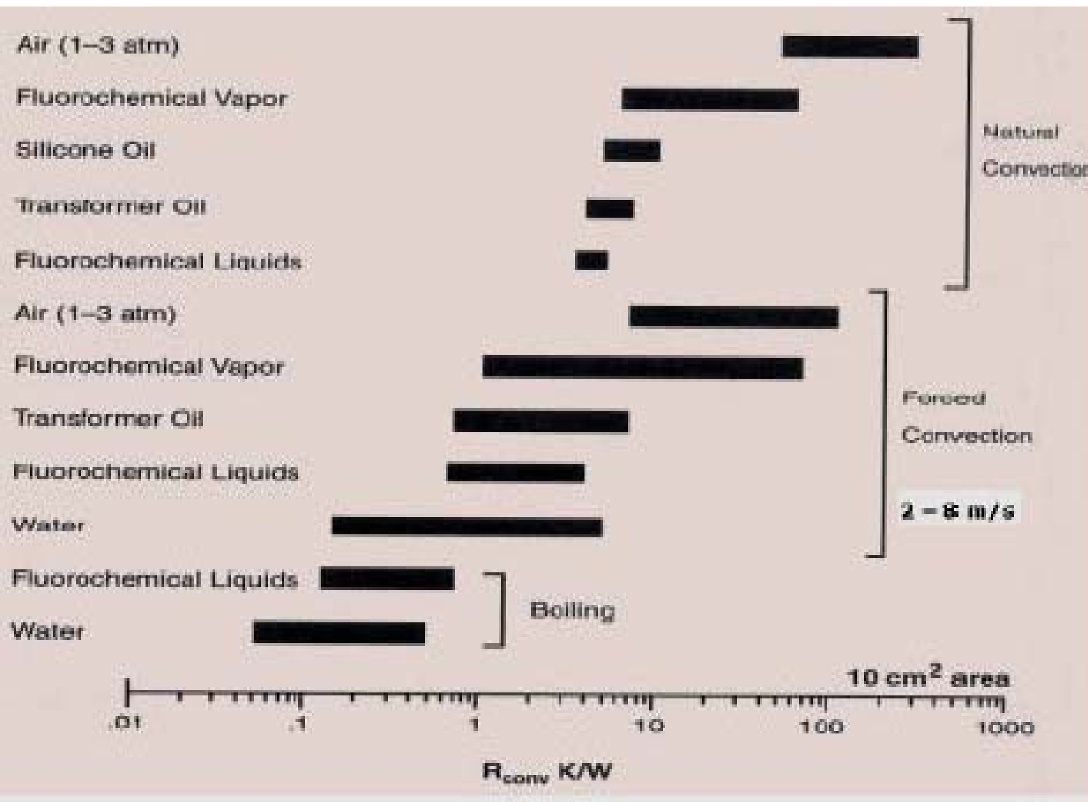
“Newton’s Law of Cooling”

$$\Delta T = \frac{QL}{AK}$$



Give me low Delta P and Low Delta T

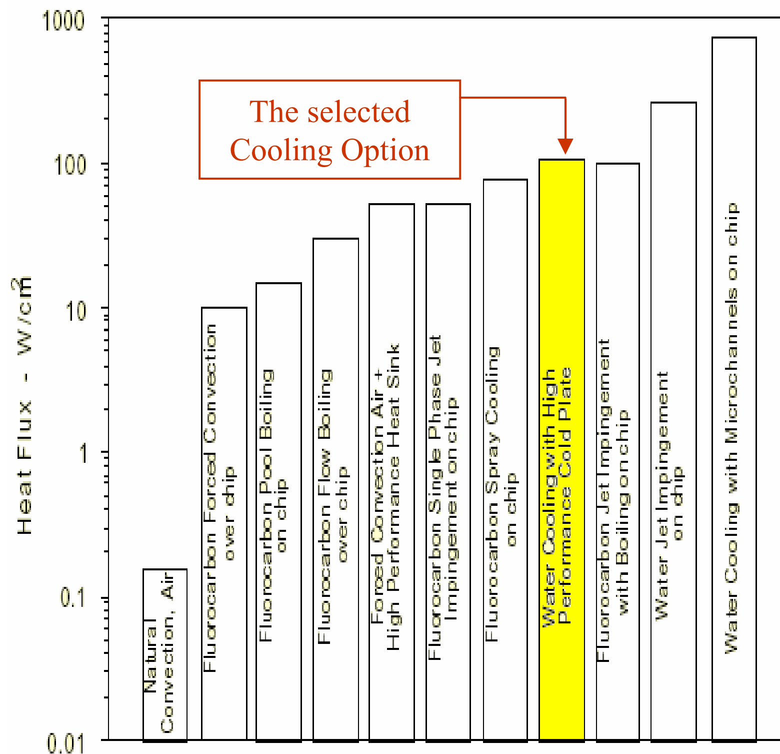
Liquid Cooling Capacity



Description	Heat Transfer Coefficient (W/m^2K)
Natural convection, air	3-25
Natural convection, water	15-1000
Forced convection, air	10-200
Forced convection, water	50-10,000
Condensing steam	5000-50,000
Boiling water	3000-100,000
Ultra thin film evaporation	10,000-500,000
Microchannel Cooling	10,000-1,000,000

Choice of Fluid as a key parameter

- Natural Convection Cooling
- Air-Fan Heat Sink
- Heat Pipe/PCM Chamber
- Liquid Cooling and Refrigeration Cooling



	FC-72	HFE-7100	Water
Heat of Vaporization [KJ/Kg]	88.47	125.61	2445.0
Thermal Conductivity [W/m.k]	0.057	0.061	0.661
Thermal Capacity [J/Kg.K]	1052.8	1214.2	4179.0
Surface Tension [dyne/cm]	12.0	13.6	72.0

27 times increase in H_{fg}

11 times increase in k

4 times increase in C_p

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Example Coolant Figures of Merit

Laminar Flow: $$FOM = \left(\frac{kC_p\rho}{\mu}\right)$$

Turbulent Flow: $$FOM = \left(\frac{k^{0.67}C_p^{1.33}\rho^{1.05}}{\mu^{0.72}}\right)$$

Coolant	Laminar (FOM)	Turbulent (FOM)
Water	14.207	27.688
FC-43	0.155	0.633
FC-75	0.405	1.249
FC-78	0.666	1.751
Coolanol-25	0.250	0.980
Coolanol-45	0.071	0.0397
Glycol/water	1.382	4.482
PAO	0.222	0.950

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Current Project Objectives

- Investigate the performance of micro-grooved surfaces for improved two-phase heat transfer using force-fed evaporation and condensation
- Achieve 100,000 W/m2K evaporation heat transfer coefficient at 200 W/cm2 heat flux
- Achieve 40,000 W/m2K condensation heat transfer coefficient
- Develop a self-contained, 2 kW line-replaceable cold plate

Definitions

- Mehendail et al. (2000) classified channels based on their hydraulic diameter *Dh*:
  - ***micro*** heat exchangers: ***Dh*** = 1-100 μm
  - ***meso*** heat exchangers: ***Dh*** = 100 μm – 1 mm
  - ***compact*** heat exchangers: ***Dh*** = 1- 6 mm
  - ***conventional*** heat exchangers: ***Dh*** > 6 mm
- Kandlikar and Grande (2003) proposed another classification based on flow phenomenon and fabrication technology:
  - ***microchannels Dh =*** 10 -200 μm
  - ***minichannels Dh*** = 200 μm - 3mm
  - ***conventional channels Dh*** above 3 mm

Microchannels

- High heat transfer coefficient (up to 500,000 W/m^2)
- High surface to volume ratio (A/V = $2*10^4$ …$4*10^5$ m^2/m^3)
- High pressure drop (10…300 MPa/m)
- Limited microchannel length (1 to 60 mm)
- Major use for cooling of high heat flux electronics
- Mostly single phase cooling
- In two-phase electronic cooling, high pressure drop in evaporator creates significant saturation temperature change, particularly with low-pressure refrigerants, effecting the performance and reliability of electronics
- High pressure drop is not affordable for condensers therefore minichannels or conventional channels are used
- Potential condenser volume reduction for two-phase electronic cooling loops is not realized

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Micro-Grooved Surfaces

- Cost effective fabrication using Micro-deformation Technology (Wolverine Tube, Inc.)
- Can be fabricated from any material with ductility more than 20%
- Channel width as low as 5 microns and aspect ratio of 20 is possible

Surface Dimensions: Specified (Actual)

Surface Name	A	B	C	D	E	F
Material	Mo	Cu	Cu	Cu	Mo	Mo
Fins Per Inch (FPI)	200	400 (409)	400 (409)	800 (645)	400	400
Channel Width (μm)	42	21 (22)	21 (22)	10.5 (15.2)	21	21
Fin Thickness (μm)	84	42 (40)	42 (40)	21 (22)	42	42
Channel Height (μm)	483	242 (233)	483 (415)	242 (235)	242	483
Channel Aspect Ratio	11.5	11.5 (10.6)	23 (18.9)	23 (15.4)	11.5	23

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Micro Grooved Surfaces

- Cost effective fabrication using Micro-deformation Technology (Wolverine Tube, Inc.)
- Can be fabricated from any material with ductility more than 20%
- Has a channel width as low as 5 microns, and has a possible aspect ratio of 20

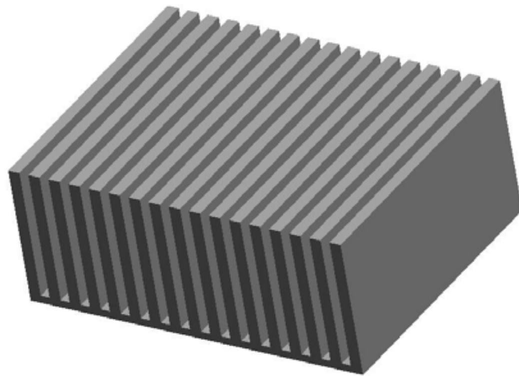


Diagram of micro-grooved surface

Dimensions of tested micro-structured surfaces

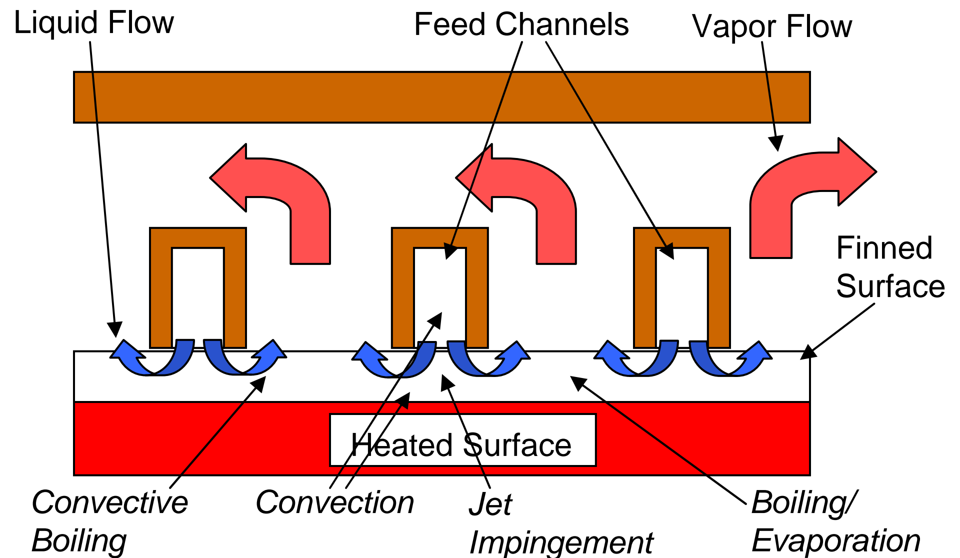
Surface #	FPI	Fin Pitch (mm)	Fin Height (mm)	Channel Width (mm)	Channel Aspect Ratio (H/W)	Fin Thickness (mm)
9	100	0.254	0.456	0.084	5.5	0.169
10	100	0.254	0.660	0.084	8.0	0.169
11	**100**	**0.254**	**0.889**	**0.084**	**10.6**	**0.169**
14	143	0.178	0.838	0.059	14.0	0.118
17	**200**	**0.127**	**0.483**	**0.042**	**11.5**	**0.085**

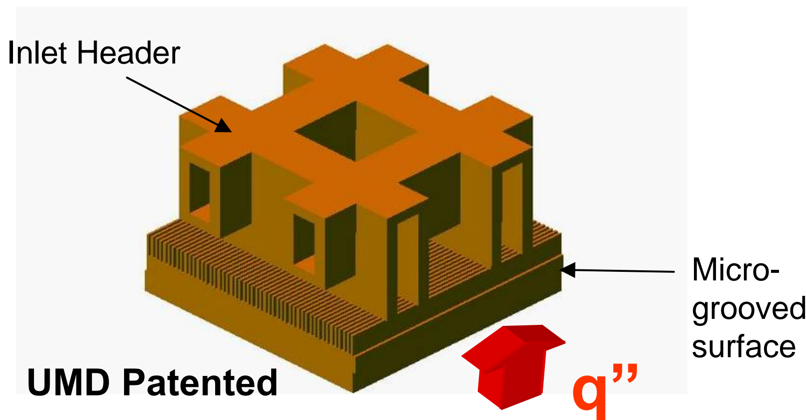
Comparison Study

- **High aspect ratio single minichannel 2800 x 400 μm, *Dh* = 725μm 200 mm long**
- **Microgrooved surface with 889 x 84 μm grooves, *Dh* = 175 μm**
- **Three refrigerants: HFE 7100, R 245fa, R 134a**

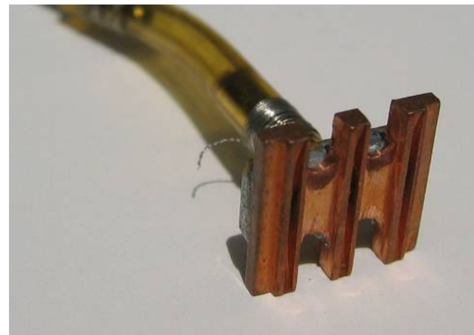
Forced-Fed Evaporation

- Forces incoming liquid under escaping vapor to raise channel 'dry-out' heat flux when boiling on finned surfaces
- Accomplished by an inlet header feeding liquid to the surface

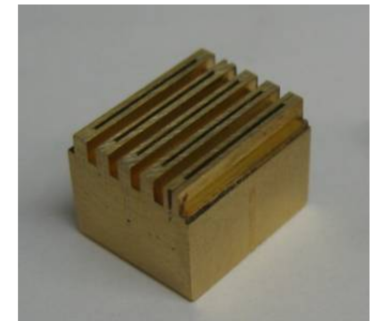




First Generation Header



Second Generation Header



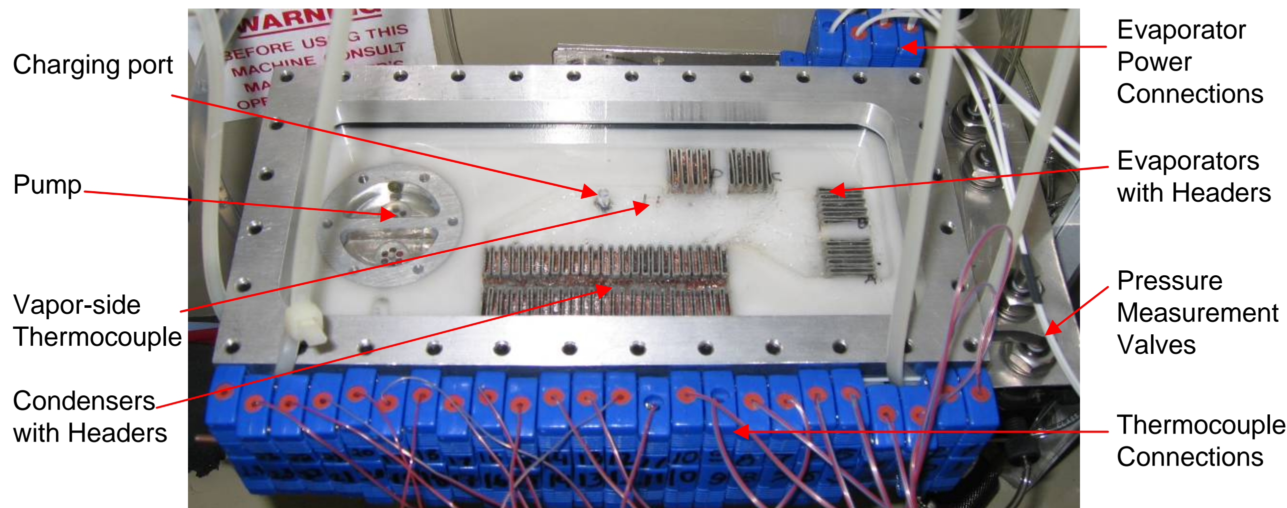
Refrigerants

- Two refrigerants were used for testing
  - HFE 7100 – evaporation, condensation
  - R-245fa – condensation
- Low toxicity, low global warming

Property	HFE-7100	R-134a	R-245fa	Water
Chemical Formula	C4F9OCH3	$C_2H_2F_4$	$CHF_2CH_2CF_3$	H2O
Boiling Point (1 atm) [°C]	61	-26.09	14.91	100
Density [kg/m3]	1402	1377	1366	1000
Surface Tension [dyne/cm]	12.3	15.27	-	58.91
Kinematic Viscosity [cSt]	0.38	2.74	3.43	2.94
Latent Heat of Vaporization [kJ/kg]	121.22	212.07	197.3	2257
Specific Heat [kJ/kg-K]	1.253	1.278	1.310	4.18
Thermal Conductivity [W/m-K]	0.062	0.105	0.084	0.661
Dielectric Strength [kV/mm]	11	7	-	---
Dielectric Constant	7.4	9.5	-	78.5

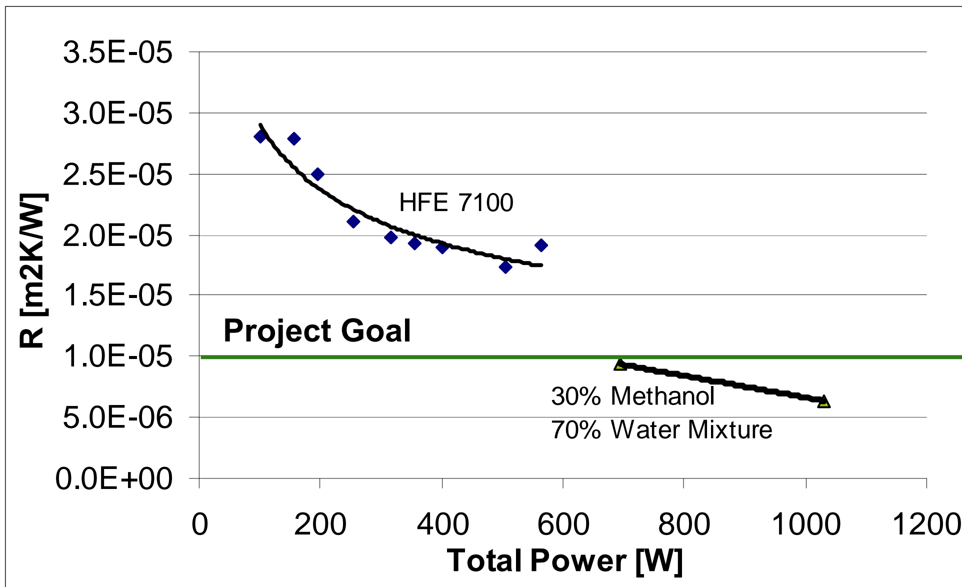
1st Generation Cold Plate Design

- Plate components:
  - Four evaporators: 14mm square, heated by 250+ W heaters
  - One pump: 250 ml/min
  - Two condensers: 10 mm by 70 mm, cooled by a water-cooled slot
- Plate dimensions are 100 mm x 200 mm; ¼ the final cold plate size
- Expected capacity is 1 kW; ½ the final cold plate capacity

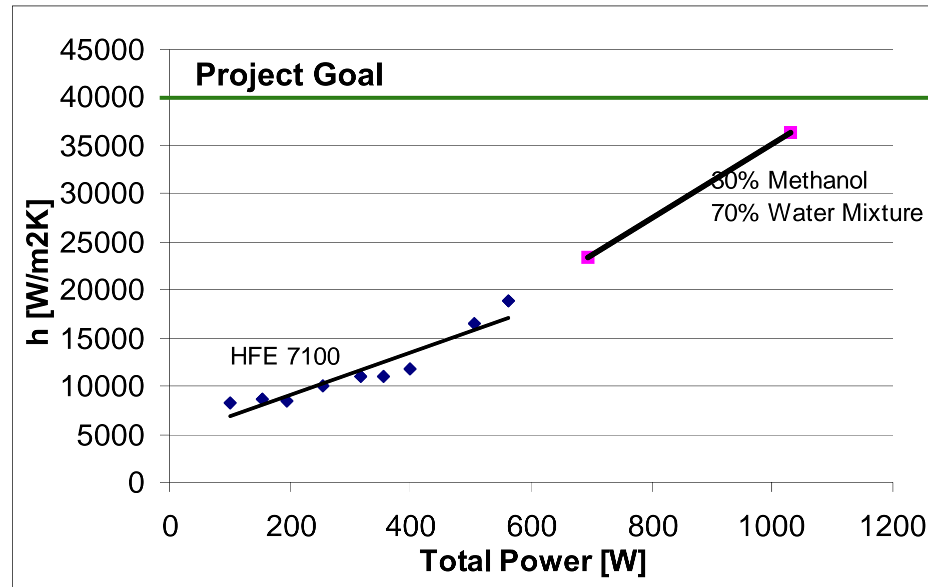


1st Generation Cold Plate Testing

Evaporator thermal resistance



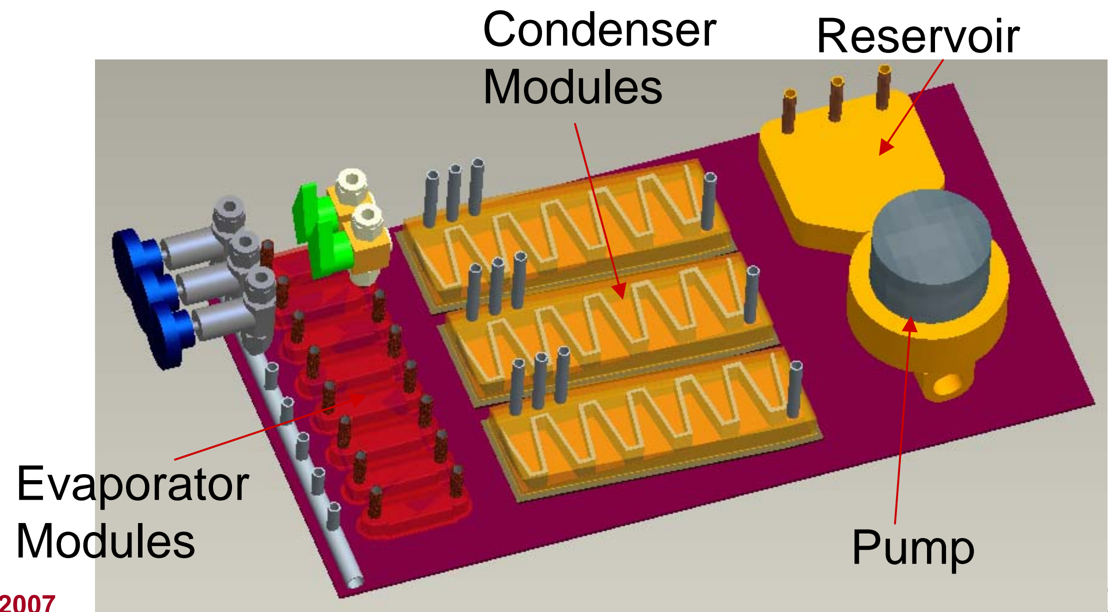
Condenser heat transfer coefficient



- Total plate power dissipation exceeds 1000 W using 30/70 methanol water mixture; equivalent to 4 kW on the full size cold plate
- Evaporator thermal resistance meets project goals
- Condenser heat transfer coefficient approaches project goal value
- Capacity is limited by instability of two-phase loop
- Condenser should be large to reject heat effectively

2nd Generation Plate Design

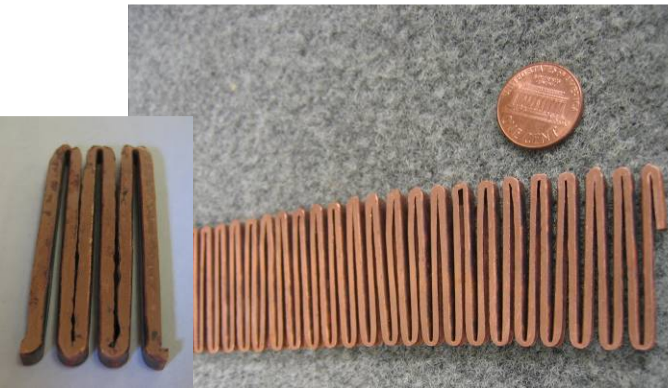
- 200 x 400 mm^2 plate with 2+ kW expected capacity
- Consists of discrete, sealed modules of evaporators and condensers
  - Up to 8 evaporators 17 mm x 34 mm
  - 2-3 condensers 34 mm x 135 mm
- Hermetic impeller pump provides surplus of flow rate
- Reservoir included to compensate fluid expansion
- Valves in liquid line to manage flow distribution

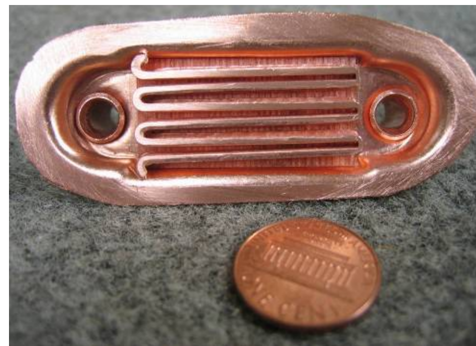


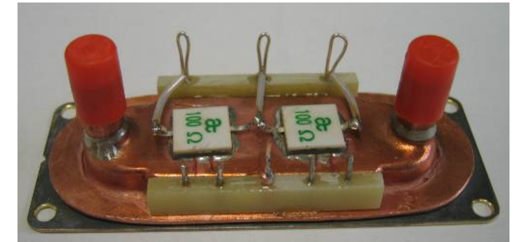
2nd Generation Plate Construction

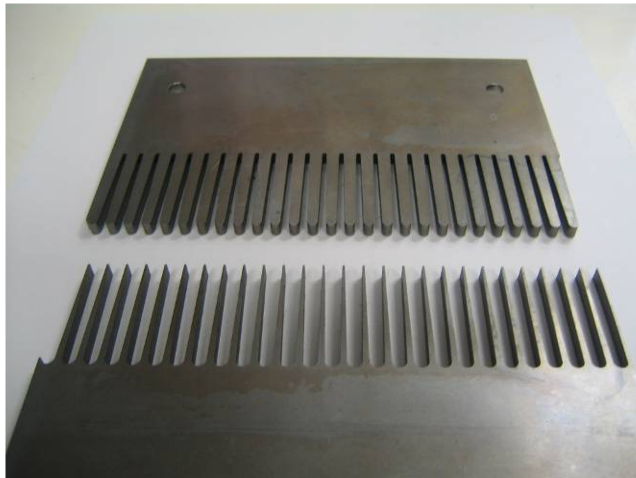
Headers constructed from bent copper with "C" cross section

Evaporator and condenser designed and constructed by stamping process



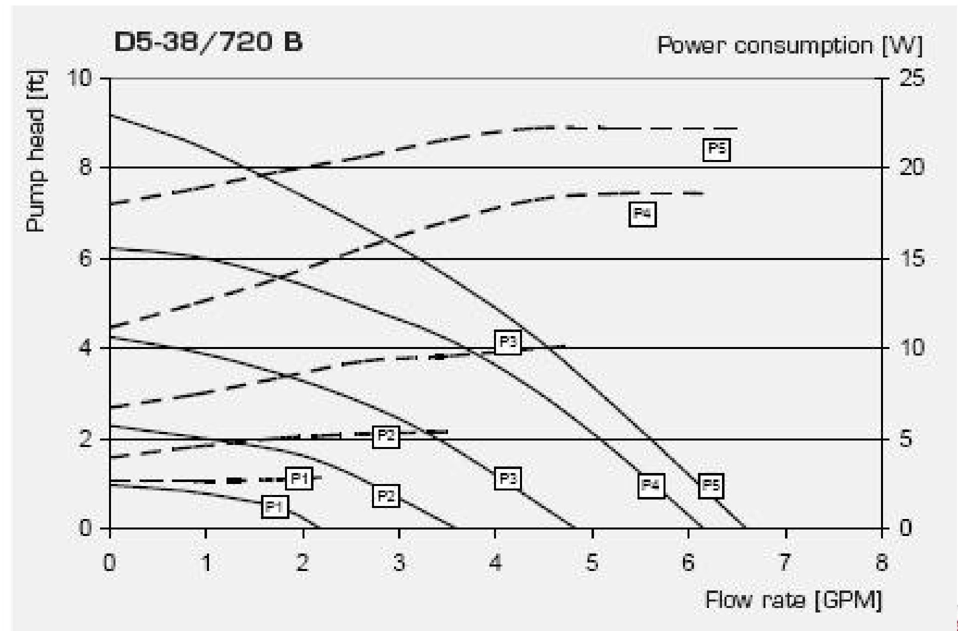




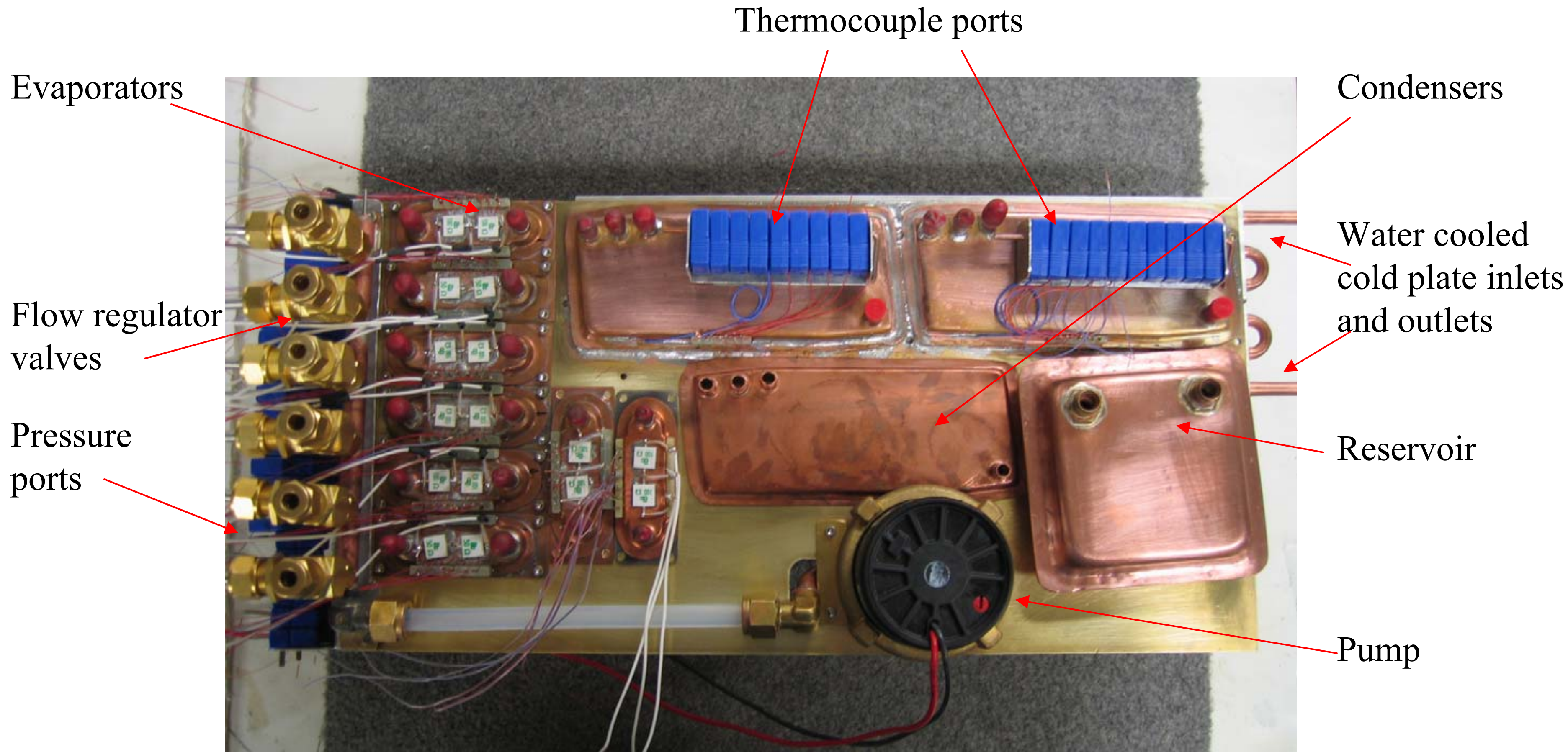


2nd Generation Cold Plate Pump

- Hermetic impeller pump manufactured by Laing, Inc.
- Designed as a water circulation pump for computer cooling, solar heating, and other applications
- Up to 6.5 GPM flow rate
- Up to 3.9 PSI pressure



2nd Generation Cold Plate



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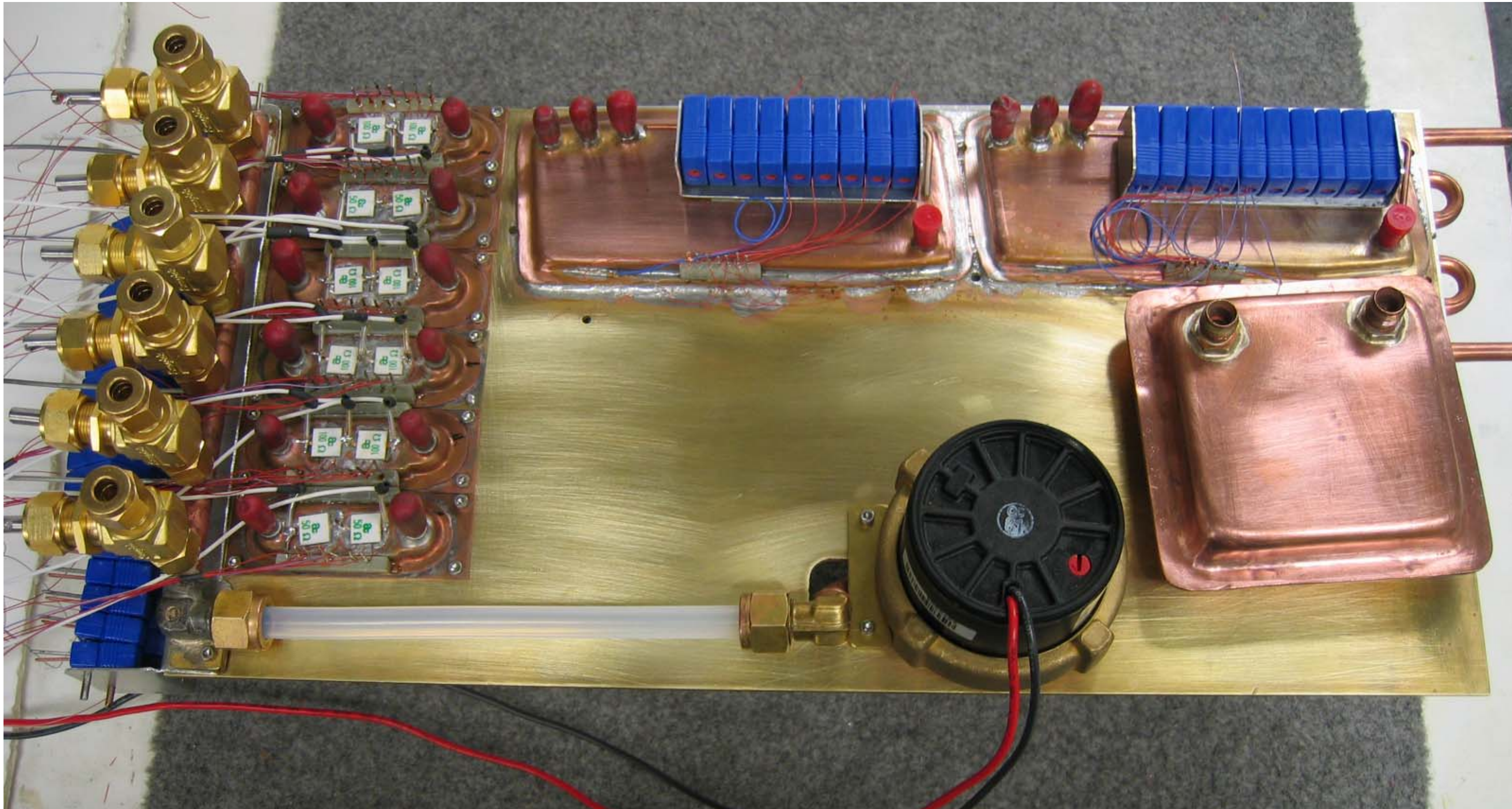
2nd Generation Cold Plate



- In the first stage of tests six evaporators and two condensers will be used

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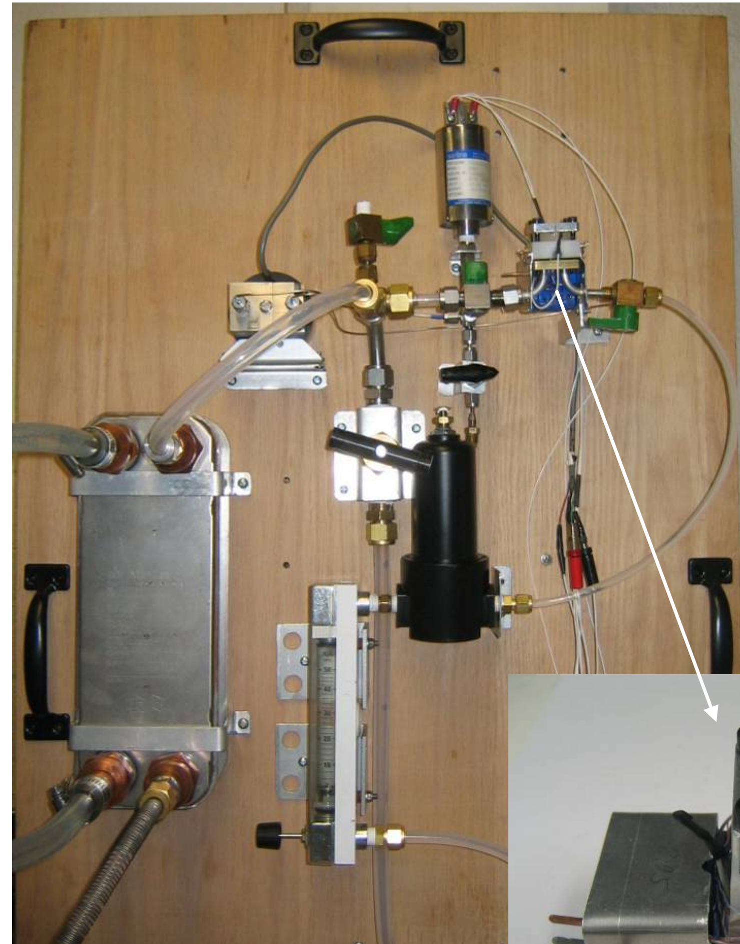
2nd Generation Cold Plate

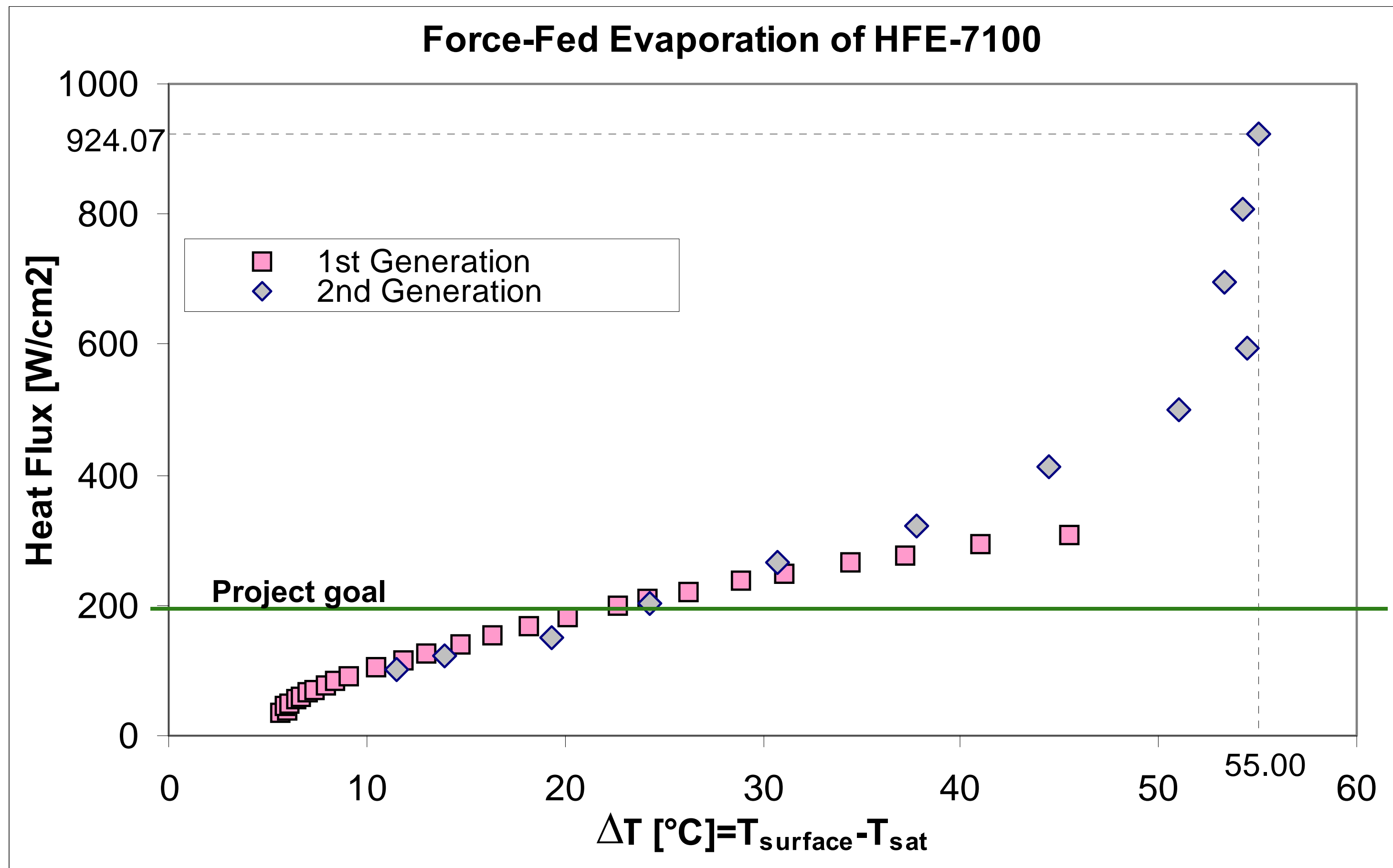
- Flexible design allows working in both horizontally and vertically positions
- Can accommodate up to eight evaporators and three condensers
- Heat rejection to cold slot
- Components can be repositioned to accommodate location of heat generation elements
- Uniform flow distribution can be achieved using flow regulator valves

Performance Testing Setup

- Designed for more detailed measurements
  - Fluid inlet and outlet temperature
  - Evaporator pressure drop
  - Flow rate
- Permits sub-cooled boiling tests
- Designed for higher capacity – 2kW goal

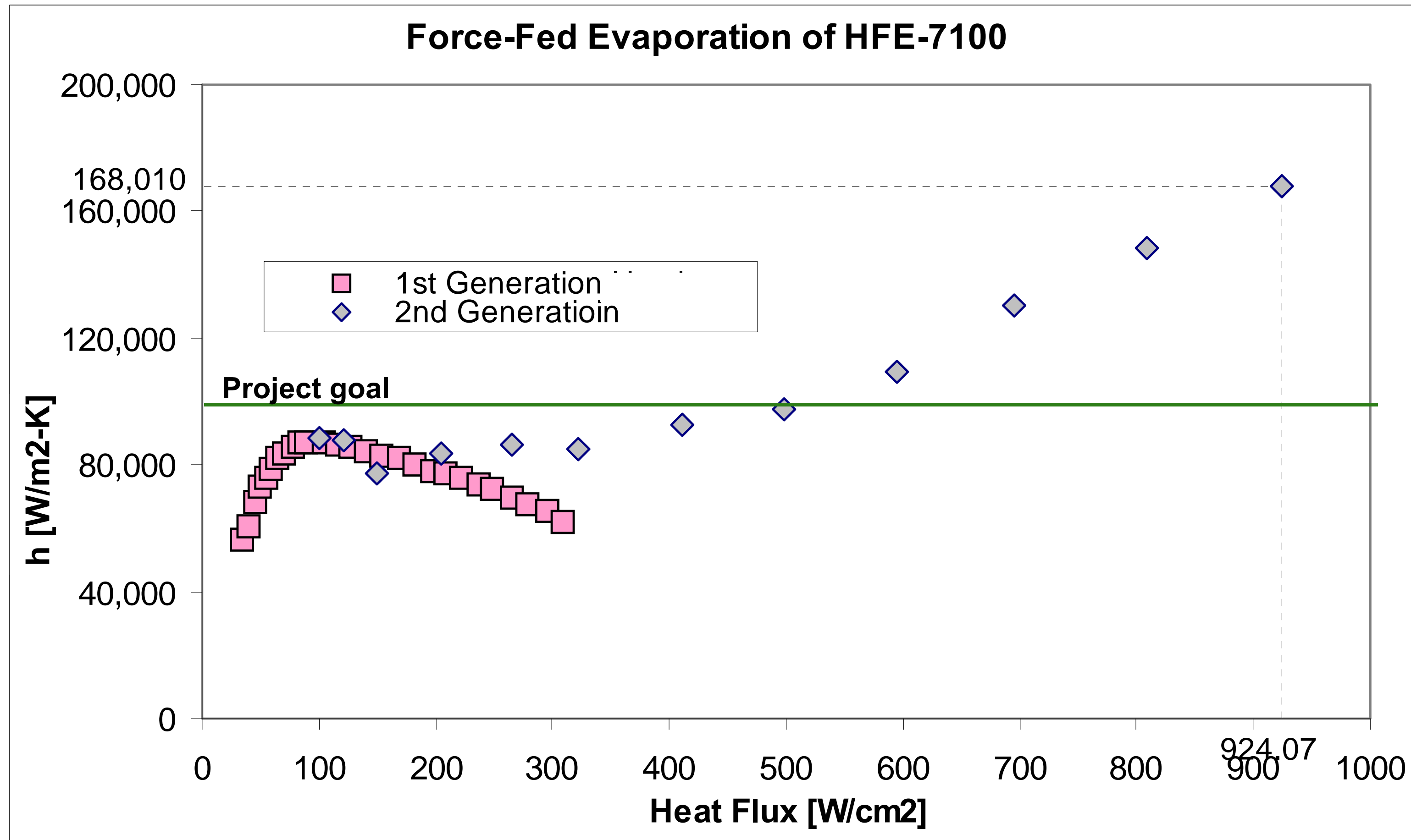


Force-Fed Evaporation



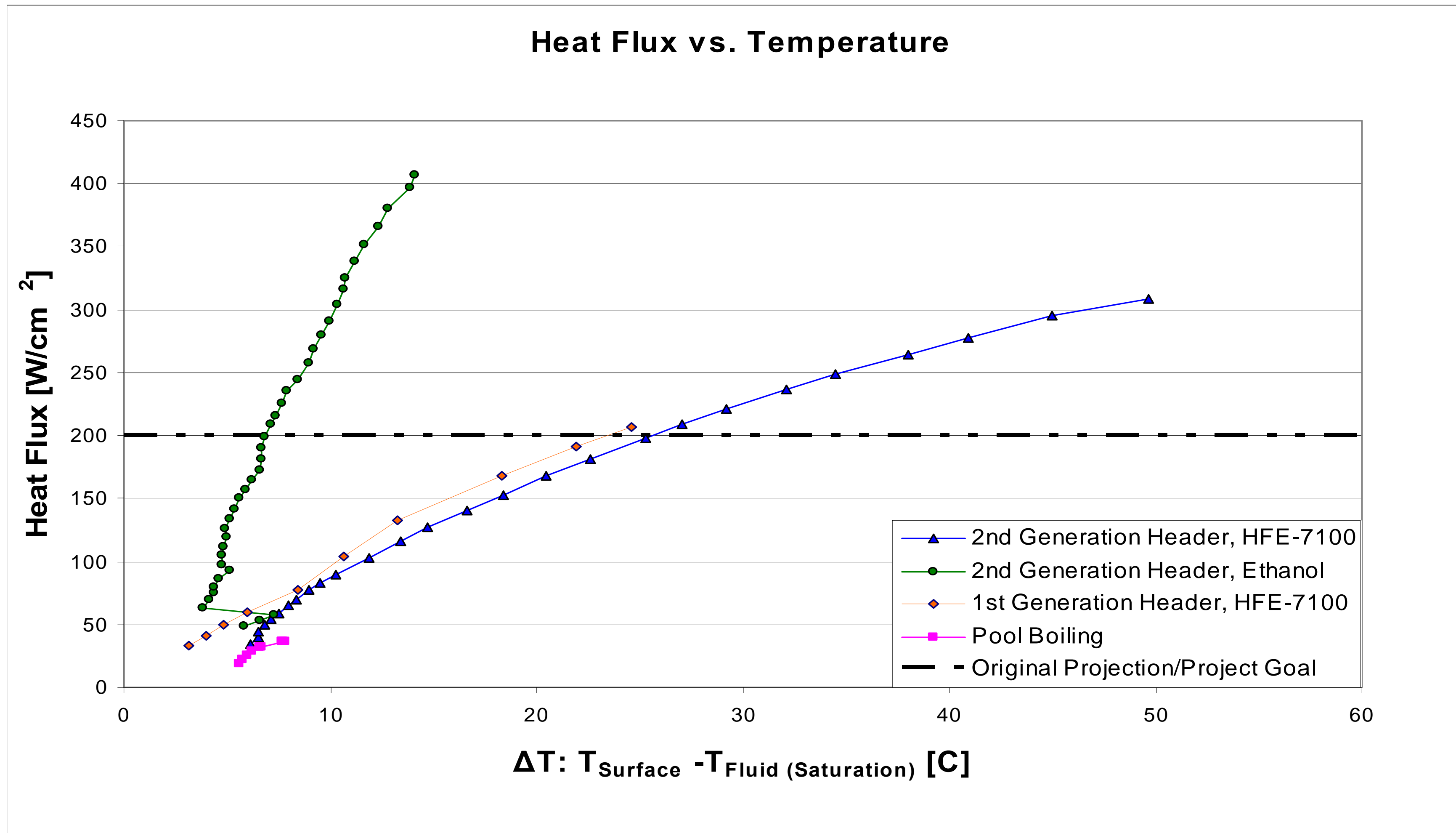
Sample #17 Data

Force-Fed Evaporation



Sample #17 Data

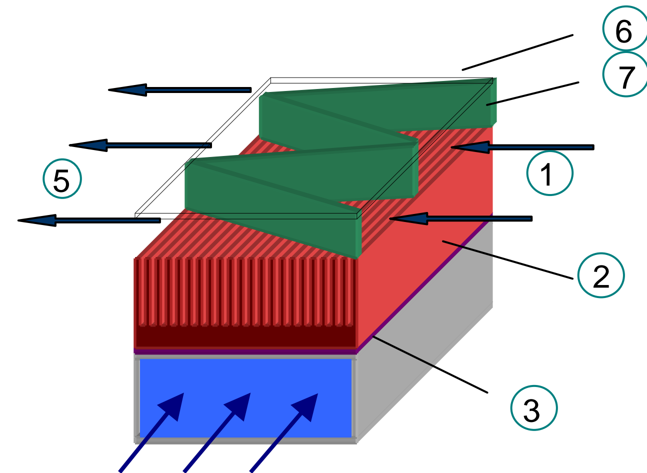
Force-Fed Evaporation Data for Sample 17



Microgrooved Surface Condenser

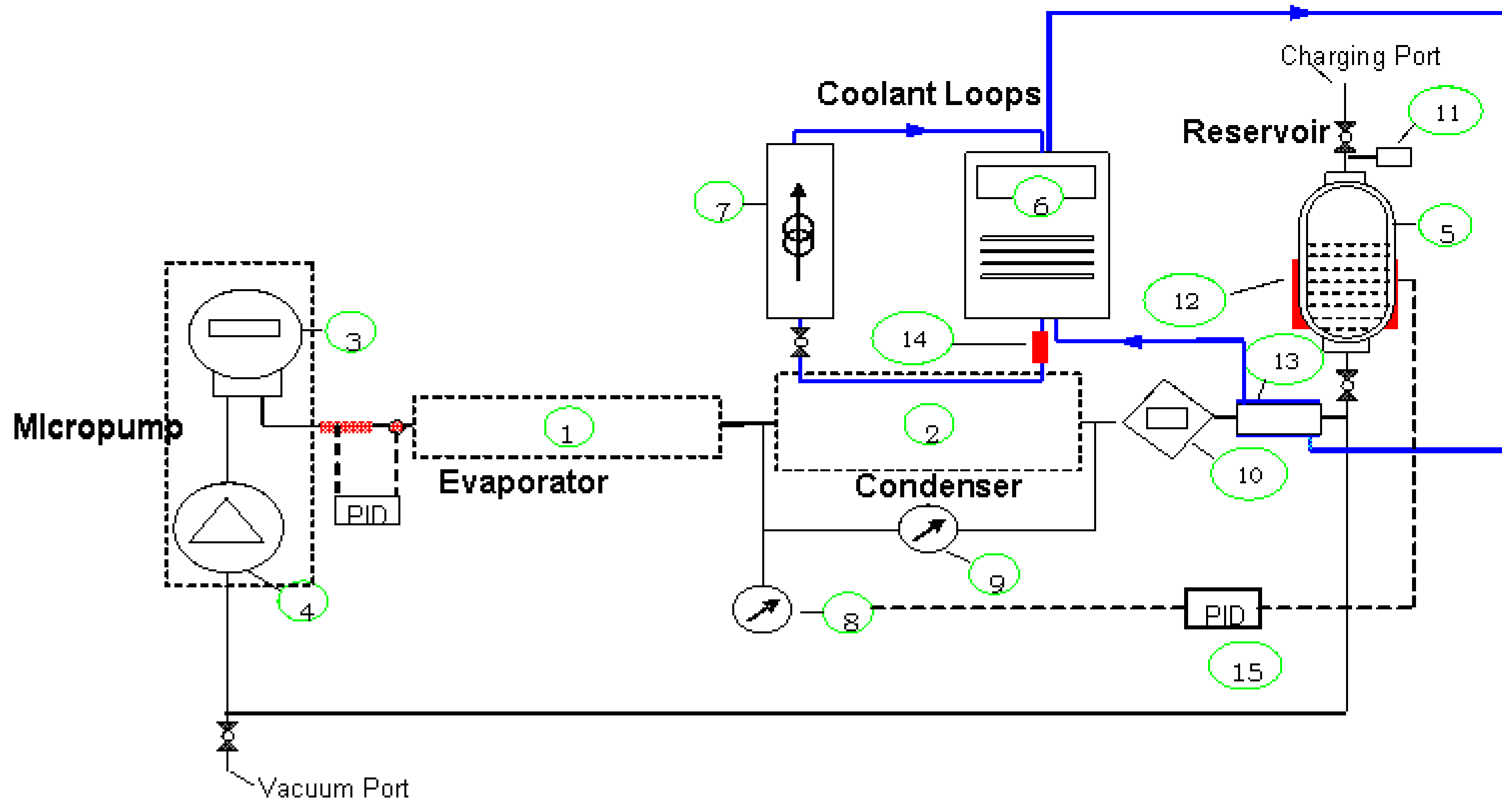
Recent UMD development

- Uses a combination of micro grooved surface with a developed system of feed channels
- Combines high heat transfer of microchannels with low pressure drop
- Is suitable for cooling large surfaces
- Is based on low production cost of micro groove surfaces



1. Refrigerant inlet ;
2. Micro grooved surface;
3. Solder;
4. Chiller water;
5. Refrigerant outlet;
6. Glass; 7. Zigzag header.

Condenser Test Setup



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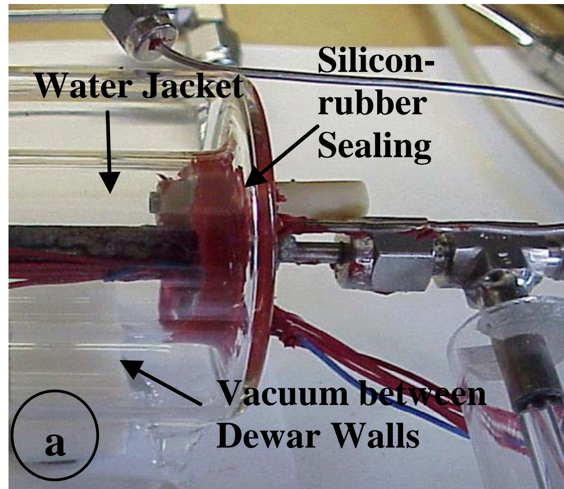
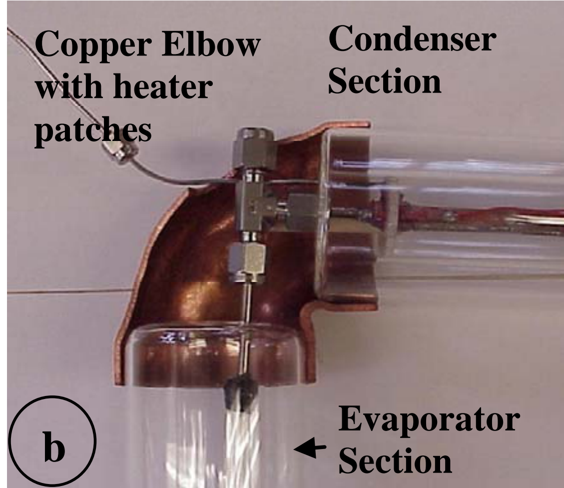
Minichannel Setup Components





Microchannel Condenser

Condenser Section

Sight Glass

Evaporator
Section

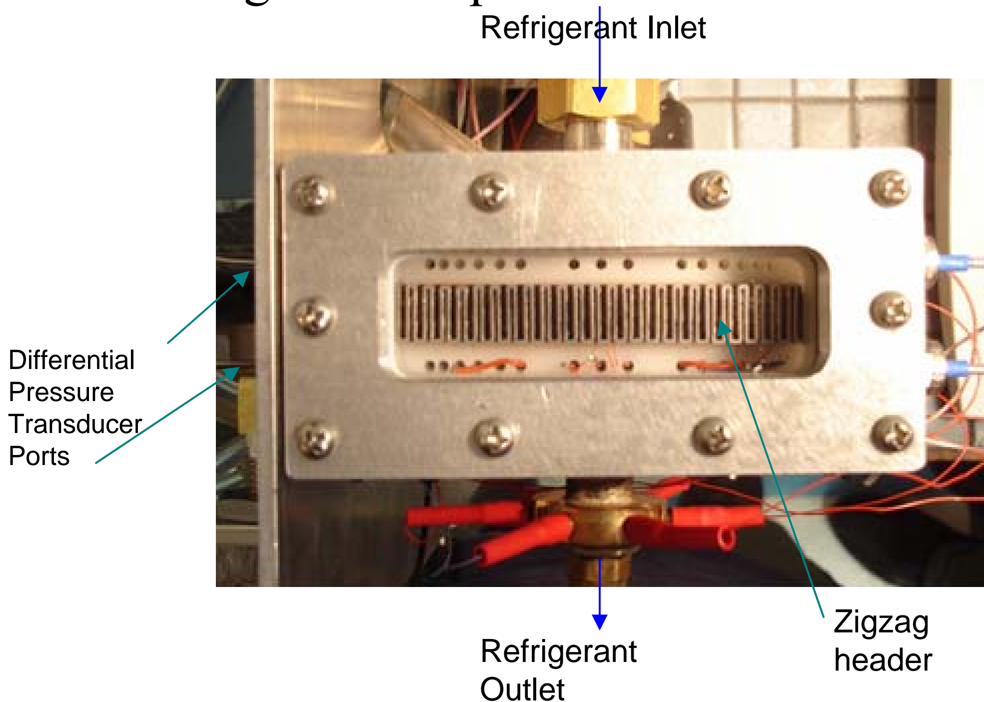
Double-wall
Dewar
Cylinder

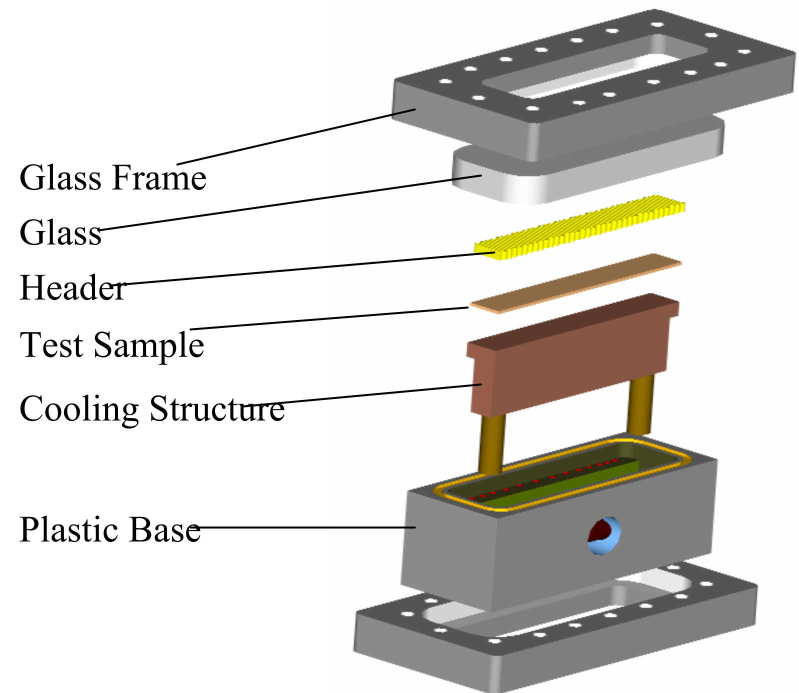
Sub-cooler

c

Condenser Test Section

- Tested micro grooved surface of 70 mm x 10 mm dimensions.
  - –Header made of soft solder alloy with wall thickness of 0.5 mm
  - –Glass top for visualization
  - –Easy to change and test various surfaces and headers
- Five thermocouples on the micro grooved surface and two for inlet and outlet refrigerant temperatures

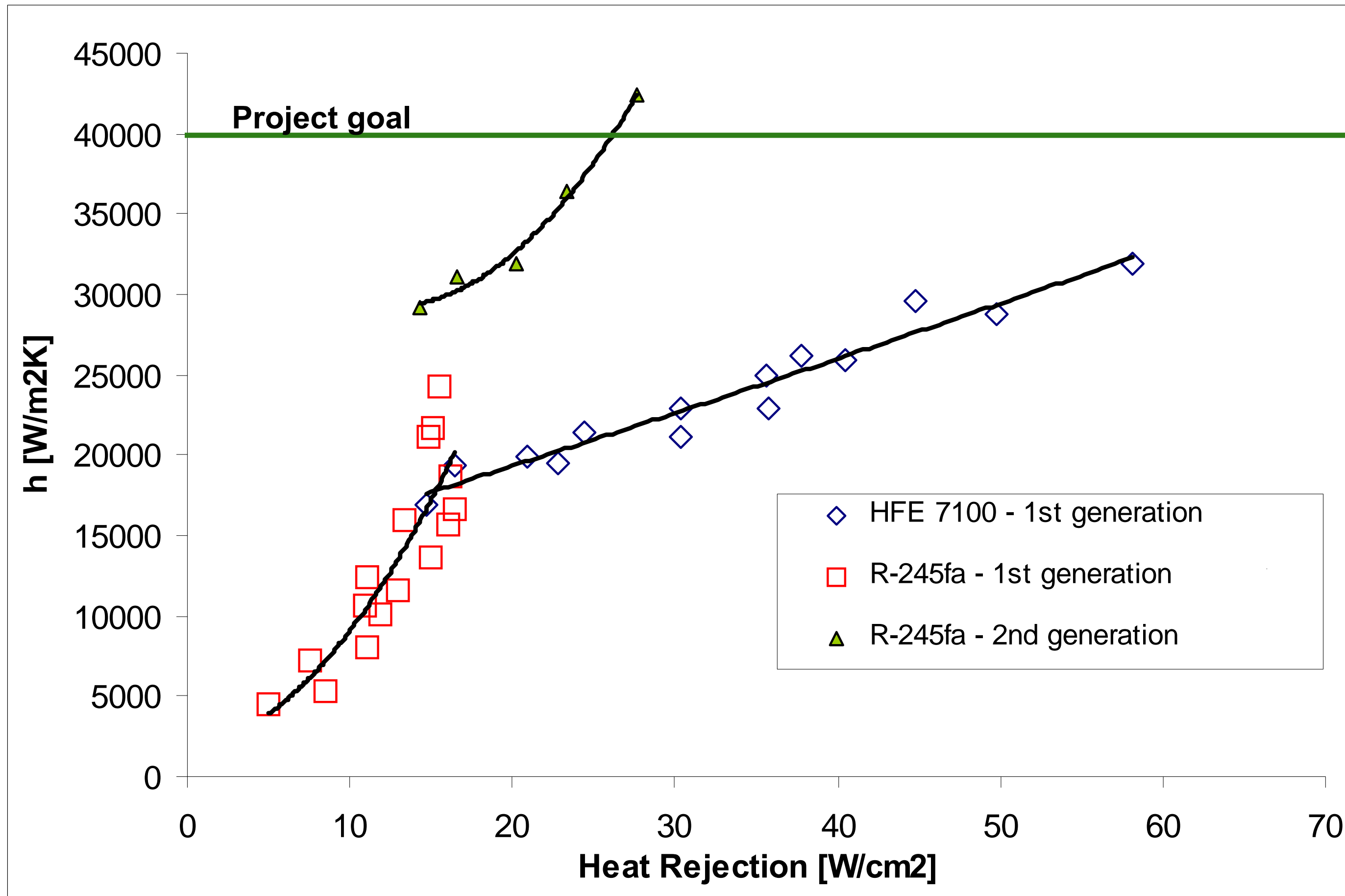




Properties of Fluids

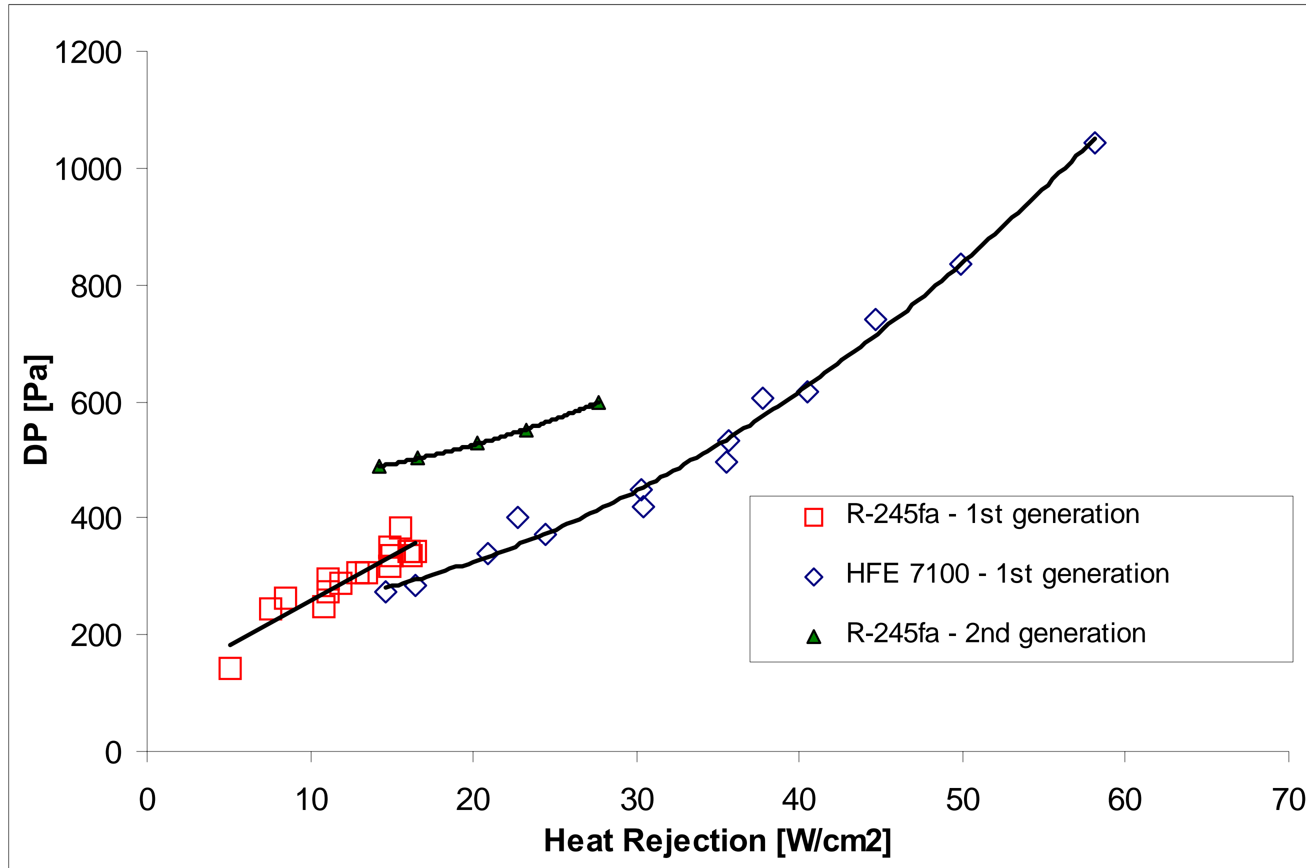
Property	HFE-7100	R-134a	R-245fa	Water
Chemical Formula	$C_4F_9OCH_3$	$C_2H_2F_4$	$CHF_2CH_2CF_3$	H_2O
Boiling Point (1 atm) [°C]	61	-26.09	14.91	100
Saturation pressure at 20°C [kPa]	22.3	571.59	124	2.34
Saturation pressure at 80°C [kPa]	173.2	2633.1	788	47.37
Density [kg/m3]	1402	1377	1366	1000
Surface Tension [dyne/cm]	12.3	15.27	15.34	58.91
Dynamic Viscosity [mPa s]	0.65	0.38	0.47	0.28
Latent Heat of Vaporization [kJ/kg]	121.22	212.07	197.3	2257
Specific Heat [kJ/kg-K]	1.253	1.278	1.310	4.216
Thermal Conductivity [W/m-K]	0.062	0.105	0.084	0.661
Dielectric Strength [kV/mm]	11	7	-	????
Dielectric Constant	7.4	9.5	-	78.5

Force Fed Condensation



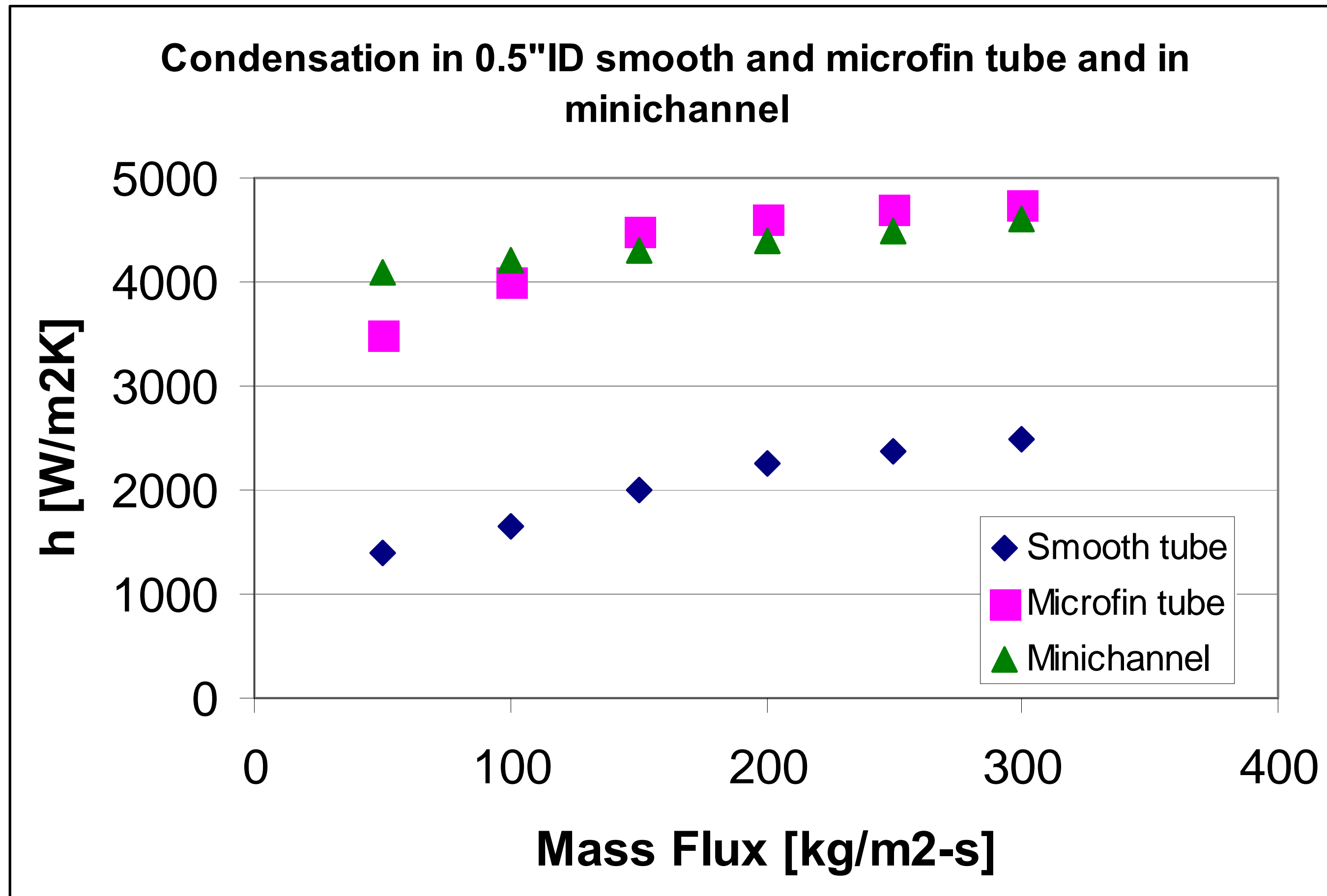
- The data points were taken for 100% inlet and 0% outlet vapor quality
- 3rd generation header was designed and fabricated

Force Fed Condensation



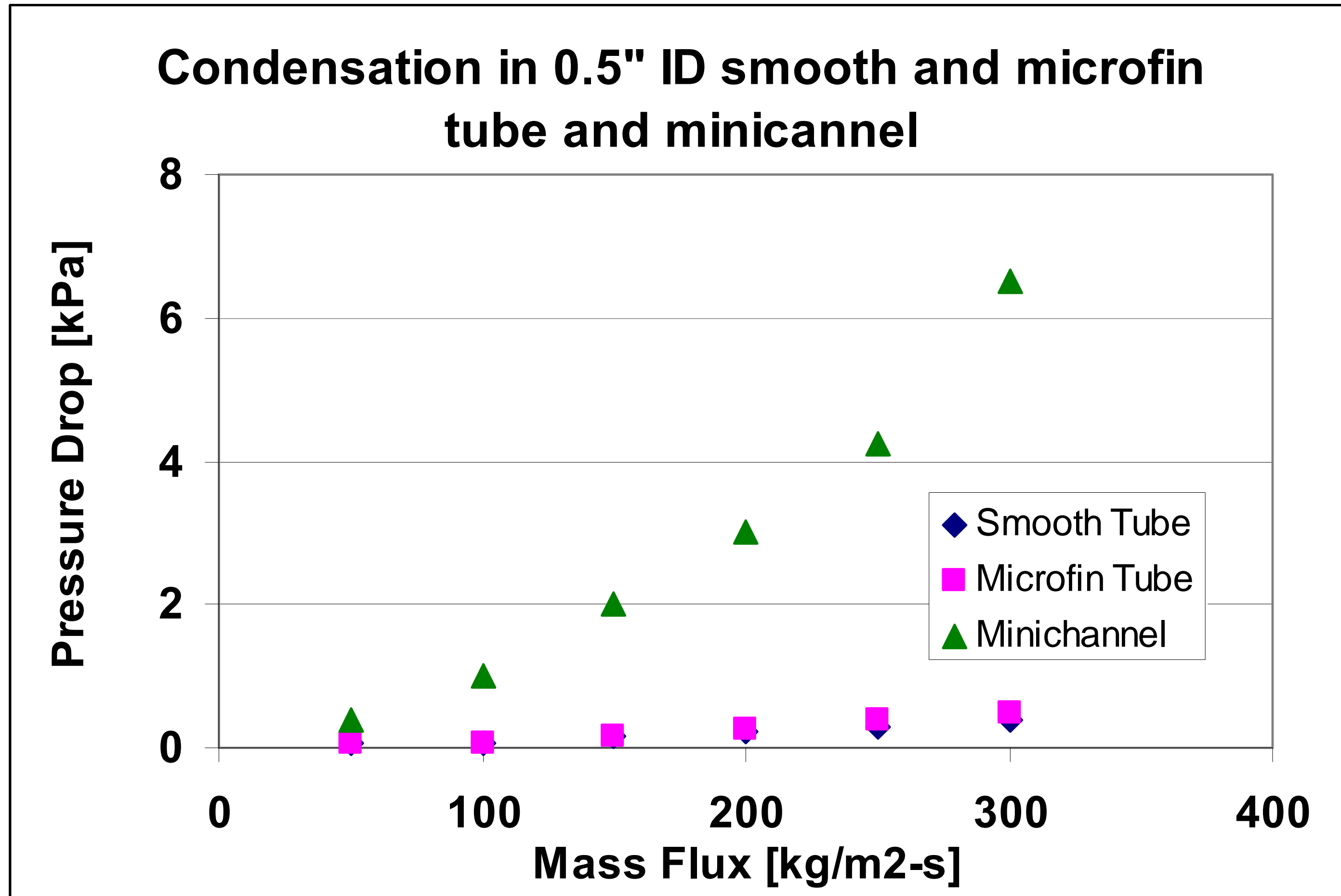
Very low pressure drop for a microscale application

Technology Comparison

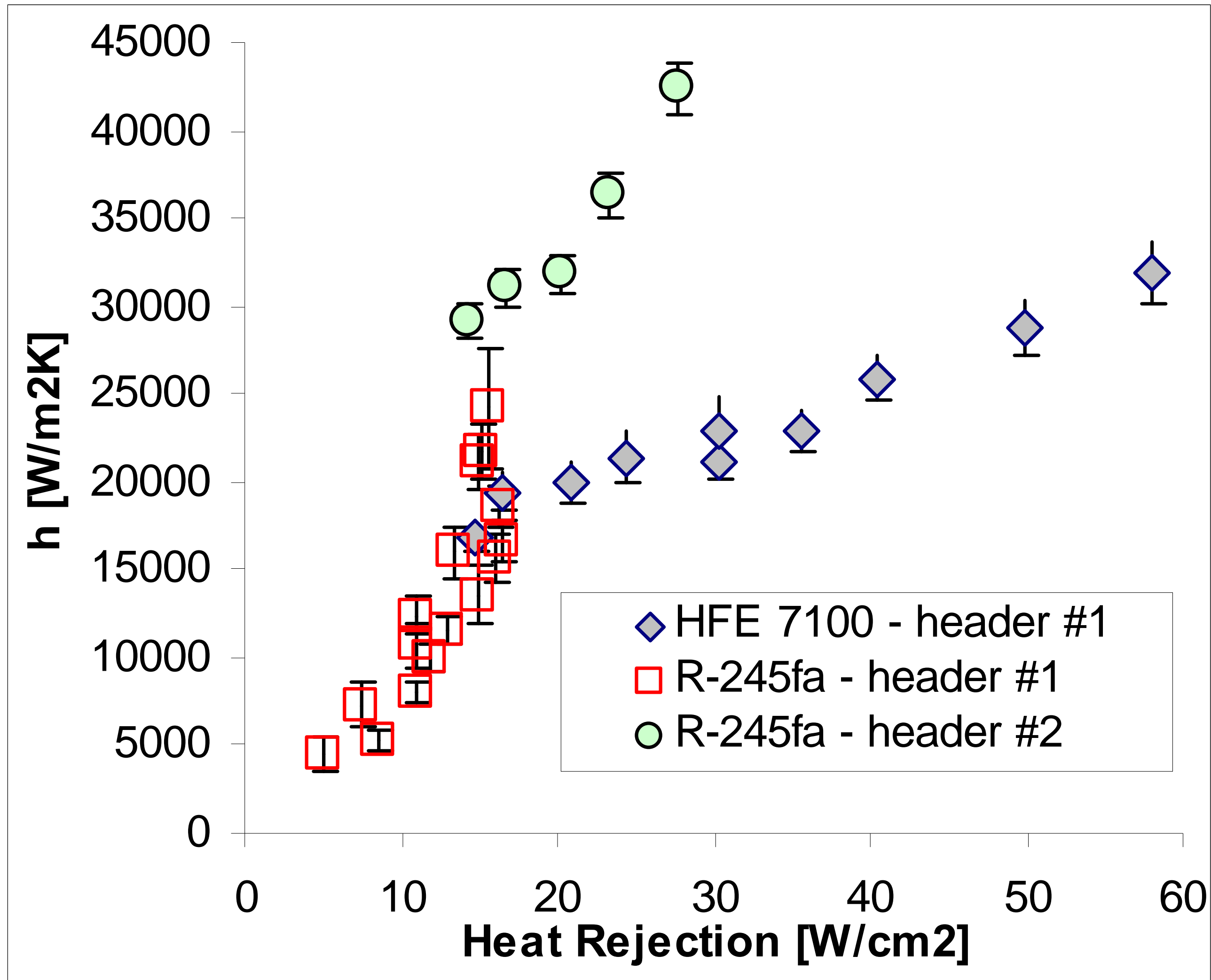


Area to volume ratio for the tube 360 m^2/m^3 , for minichannel 5500 m^2/m^3

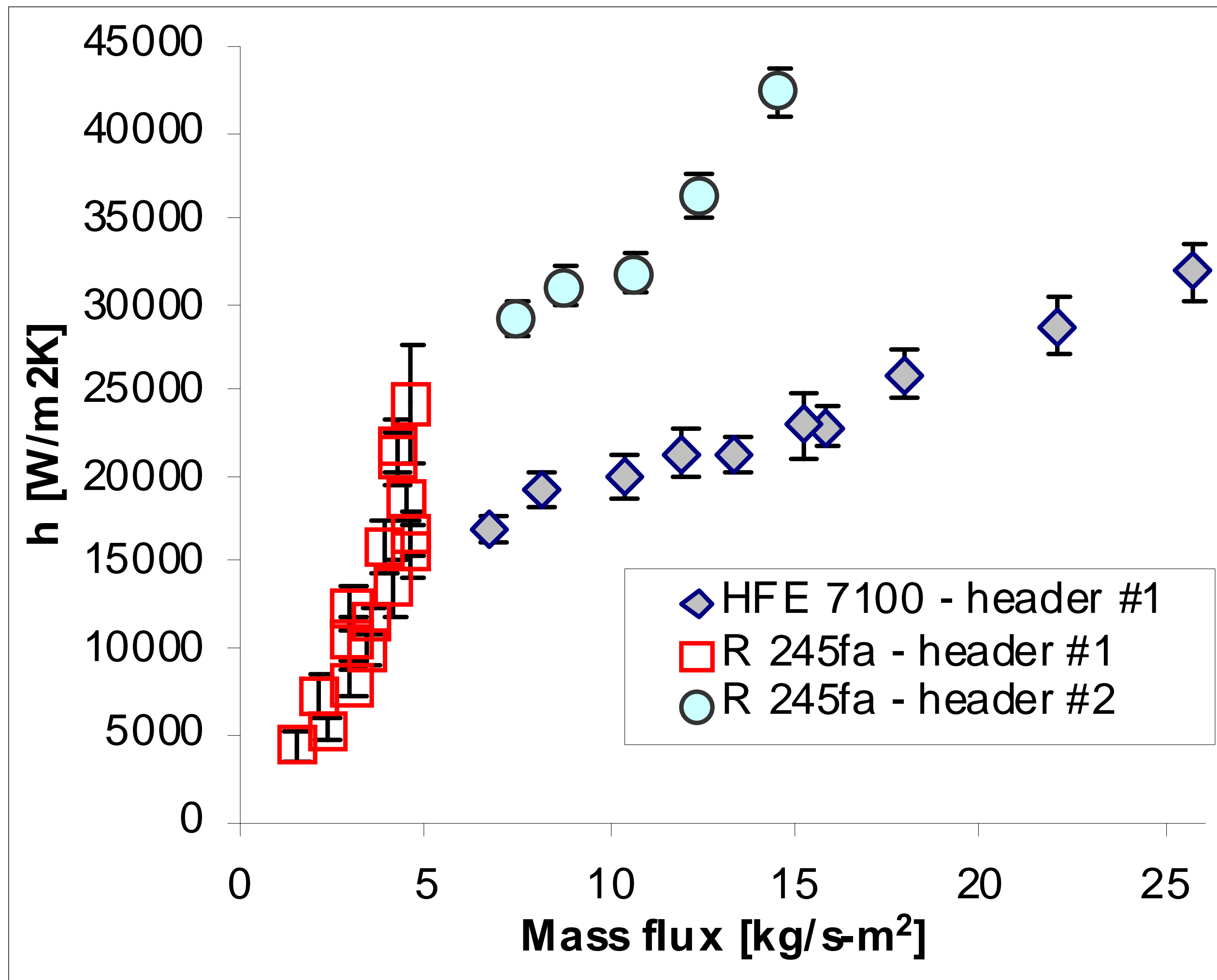
Technology Comparison



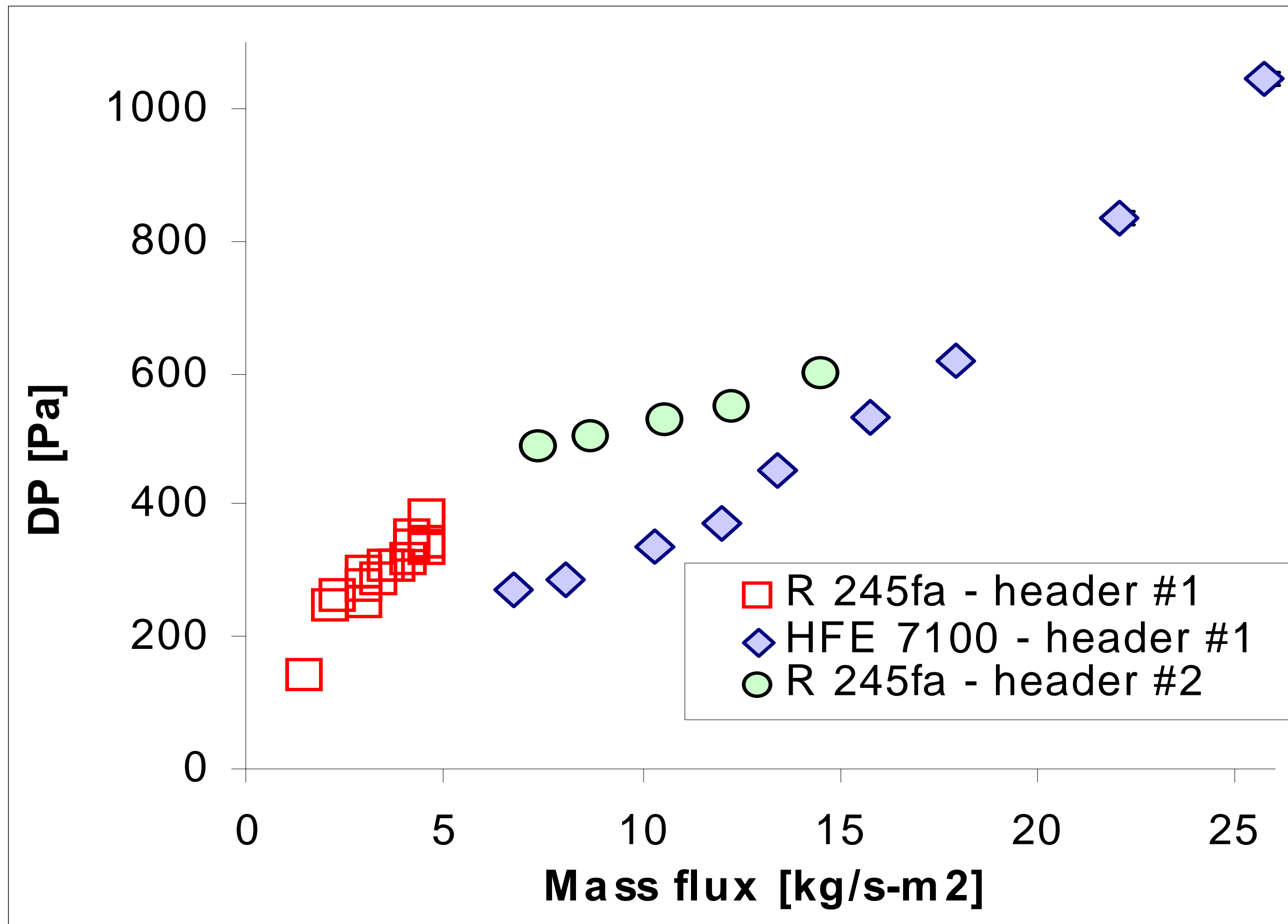
Microgrooved Surface Condenser



Microgrooved Surface Condenser

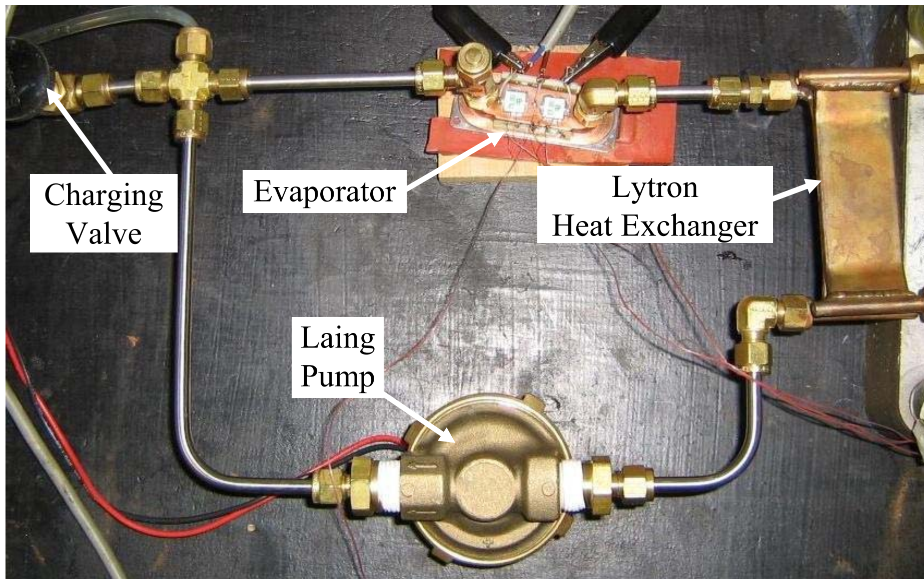


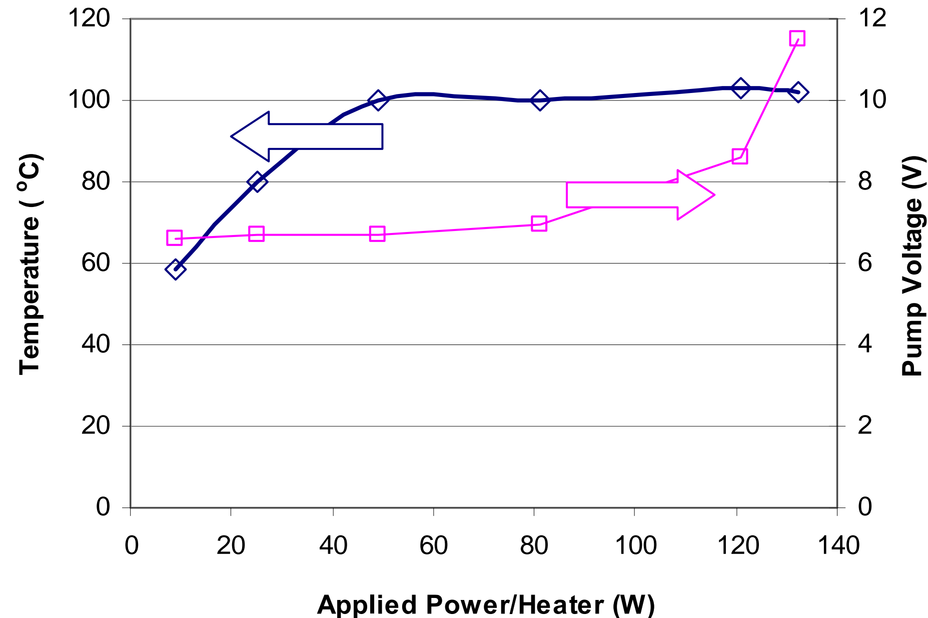
Microgrooved Surface Condenser



Pressure drop in microgrooved surface condenser depends on the header design and is independent from the condenser size

Reliability Tests





- Force fed cold plate components are under testing by ATEC for reliability analysis
- Single phase tests using EG/Water mixture
- Tests will be extended for two phase heat transfer

Conclusions

- High pressure drops often limit application of microchannel and even minichannel evaporators/condensers with low pressure refrigerants for electronics cooling
- Pressure drop in force-fed micro-grooved surface evaporators and condensers is significantly lower than their respective mini or micro channel evaporators/condensers. It also does not significantly effect condenser performance with low pressure refrigerants
- Microgrooved force-fed evaporators and condensers combine high heat transfer rate of microchannels with low pressure drops which make them an attractive alternative to conventional evaporators and condensers for two-phase electronic cooling systems

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Conclusions (Cont.)

- The 2nd generation cold plate results in the current study demonstrate potential of this technology for cost effective removal of the 1,000 W/Cm2 heat flux and appears to be applicable to both commercial and military high flux electronics

- Now that the potential of this technology has been demonstrated, it is time to understand the underlying fundamentals, thus a strong need for basic research in this area.

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Thank you

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