Technical Report EXTERNAL					
Title:	**Performance Characteristics of Ceramic and Quartz Heaters v1.3**				
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Introduction

In report CCII-00001, findings from the recently commissioned "Herschel" were presented detailing results from a selection of the Ceramicx product line. This report intends to supplement that given in CCII-00001 by including more elements from the Ceramicx product line. While not every element is tested as yet, the most popular elements are selected from each product family to give a representative idea of that group.

As a large number of elements (30) are tested, the report will thus be broken down into sections. The test includes ceramic elements and quartz elements. Product families such as the FTE are compared directly with each other in terms of power ratings (W). In addition cross comparisons are made across element family lines, such as FTE versus FFE, or FFEH to gain an understanding of the different characteristics of each group.

Test Procedure

In this automated system, an infra-red sensor is robotically guided around a pre-determined coordinate grid system in front of the heater element under test. The sensor is a Schmidt-Boelter Thermopile Heat Flux Transducer with a design maximum heat flux level of 2.3 W/cm^2. A Barium Fluoride window is attached to the sensor meaning IR in the band 0.4-10 micrometres is measured. The incident radiant heat flux recorded at each point is then saved and post processed to give a 3D representation of the infra-red heat flux emission of that heating element. At present the measurement coordinate system is a 500mm cubic grid which measures at the front of the element, see Figure 2. The robot and sensor move in 25mm increments along a serpentine path in the *x* and *z* directions, while the heating element is mounted on a slide carriage which increments in 100mm steps along the *y* direction. A spherical coordinate system is in development which will measure both in front of and behind the element. This will help to measure total element emission so as to refine the design of reflectors and hollow elements.

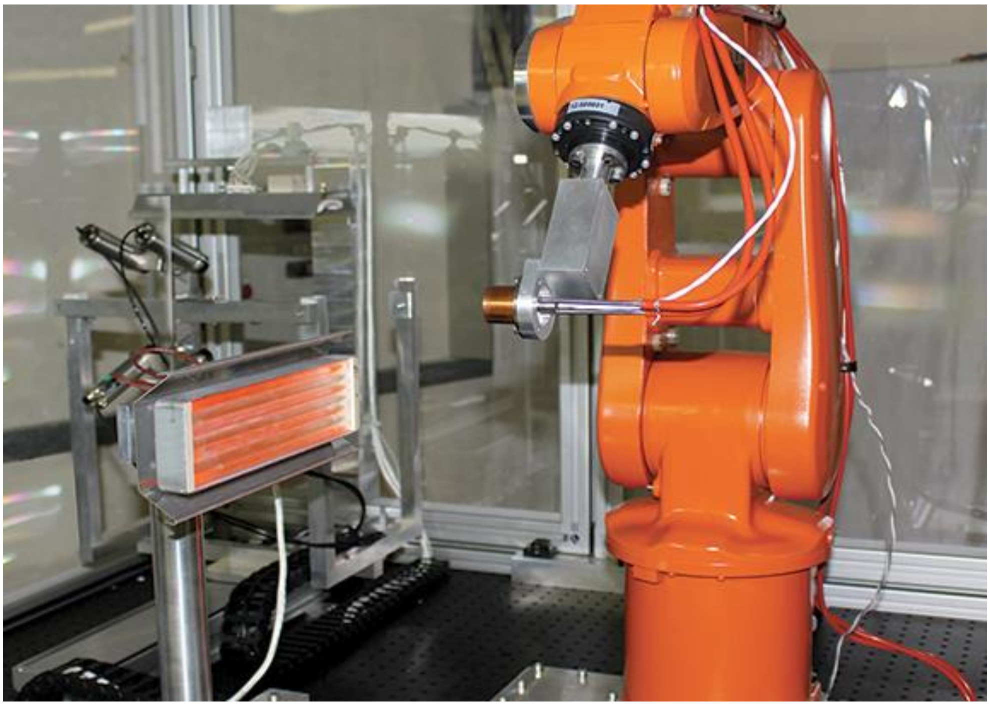

Figure 1: A quartz element under test

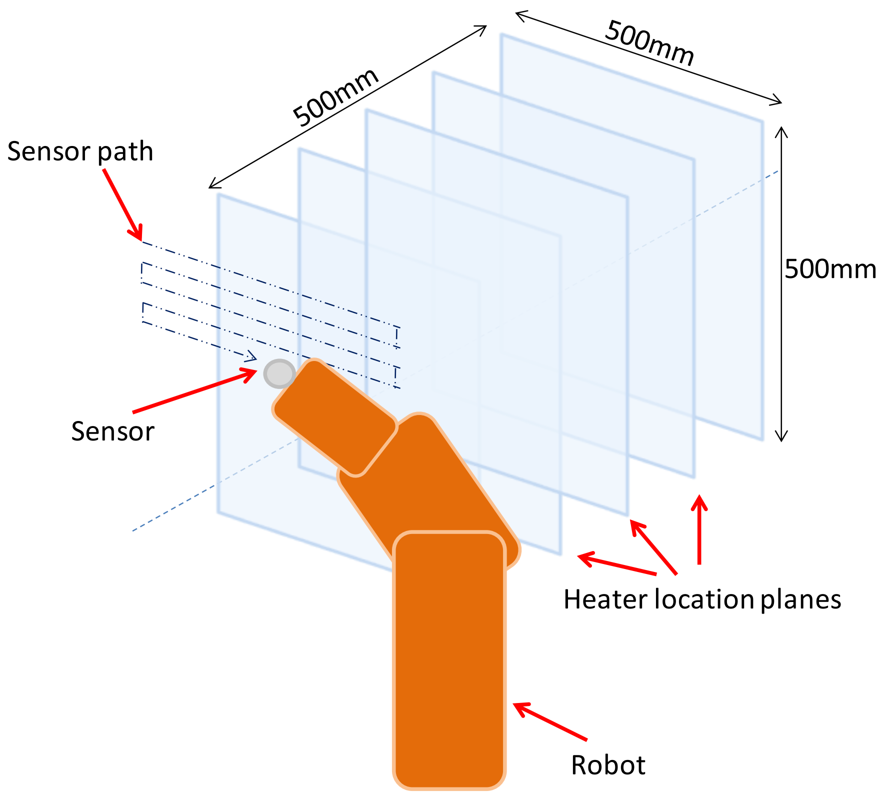

Figure 2: Schematic of measuring grid showing sensor path and planes of element location.

A complete list of the elements tested is shown in Table 1.

Table 1: List of Elements tested

ELEMENT	W	W	W	W	W	W	W
FTE	150	300		500	650		1000
HTE		325		500			
FFEH	250	300	400		600		1000
HFEH	200	300					
FFE	150	300		500			
FQE	150			500	650		1000
HQE	250	325		500			
SFSE	250		400		650	750	
SFEH	250		400		600	800	

Results and Discussion

The test results are presented in graphical format. For all elements tested, a 3D heat flux map is presented along with a percentage measurement which for the purposes of this report, is termed efficiency or η. The heat flux map shows the colour plot of the heat flux magnitudes in both horizontal and vertical planes. Due to risk of overloading the heat flux sensor and of burning the robotic arm, the minimum distance from the heater is 100mm. The percentage figure η is not a true efficiency measurement; it is a measure of what percentage of the input power is detected by the sensor within the confines of the 500 mm x 500 mm grid. It is calculated as follows

$$\eta = \frac{\phi A}{VI} \, x \, 100$$

where V is the element voltage, I is the element current in amperes, ϕ is the heat flux sensed by the heat flux sensor in W/cm^2, and A is the grid area in cm^2.

Although not a true efficiency[1,2] it shows the amount of radiated energy captured by the sensor and is nevertheless a repeatable and a useful benchmark for direct comparison of various elements. When mentioned throughout this report, it is this definition that we are referring to. As presenting all 32 tests results on one graph would be cluttered, the results are shown in stages.

[1] The grid is a finite size and therefore cannot capture all radiation emitted from the emitting element.

[2] The sensor is not always oriented towards the centre of the emitting element especially at the extremities of the grid where the emitted radiation strikes the sensor face obliquely resulting in cosine error and an under-reading of radiated heat flux.

FTE, HTE and FFE

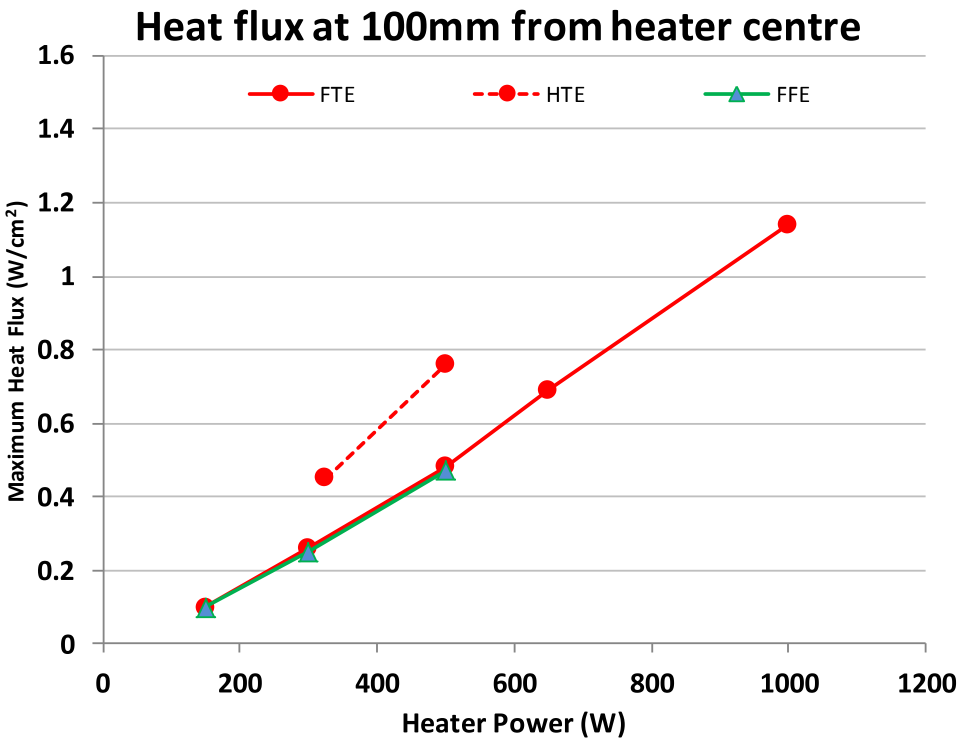

Figure 3: Maximum heat flux values at 100mm for FTE, HTE and FFE (W/cm^2)

Figure 3 summarises the maximum heat flux values for each element tested in the FTE, HTE and FFE ranges. Wattages were between 150W to 1000W. These maxima were obtained at a distance of 100mm from the emitter element surface, at the extended centreline of the element. The FTE ranges from a maxim heat flux value of 0.1 W/cm^2 at 150W increasing monotonically to 1.14 W/cm^2 at 1000W. A similar trend is seen for the FFE element although only tested up to 500W. The HTE element by comparison varies from 0.45 W/cm^2 at 325W to 0.76 W/cm^2 at 500W. Despite the HTE 500W having the equivalent power density as the FTE1000W, the maximum heat flux is still lower than that of the FTE. This is probably due to greater dispersion because of the smaller size of the half size element. However, it must be remembered these tests are carried out on single elements, and this lower maximum heat flux value may not occur in an arrayed layout. The percentage η for the FTE elements are shown in Figure 4.

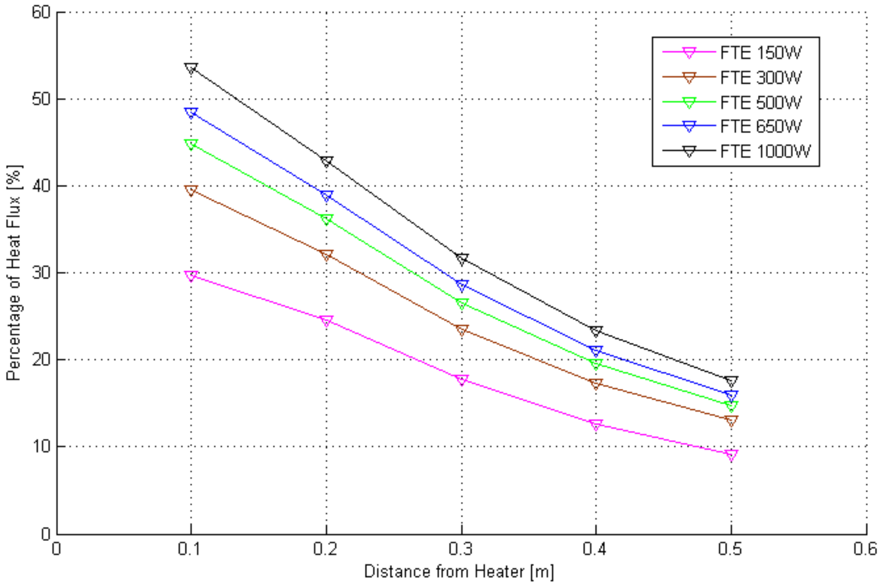

Figure 4: Percentage of input power measured at 500 x 500 mm grid, FTE range

These show that all elements radiate a substantial portion of their input electrical energy to the measuring grid at 100mm distance. For the 300W to 1000W elements this amount is from 40% to 54%. The FTE1000W element achieves the maximum at around 54% of its input energy. As the distance increases to 200, 300, 400 and finally 500mm from the heater, the amount of infrared radiation received by the IR sensor reduces, and this can be seen in all trends which decrease progressively down to around 10-18%.

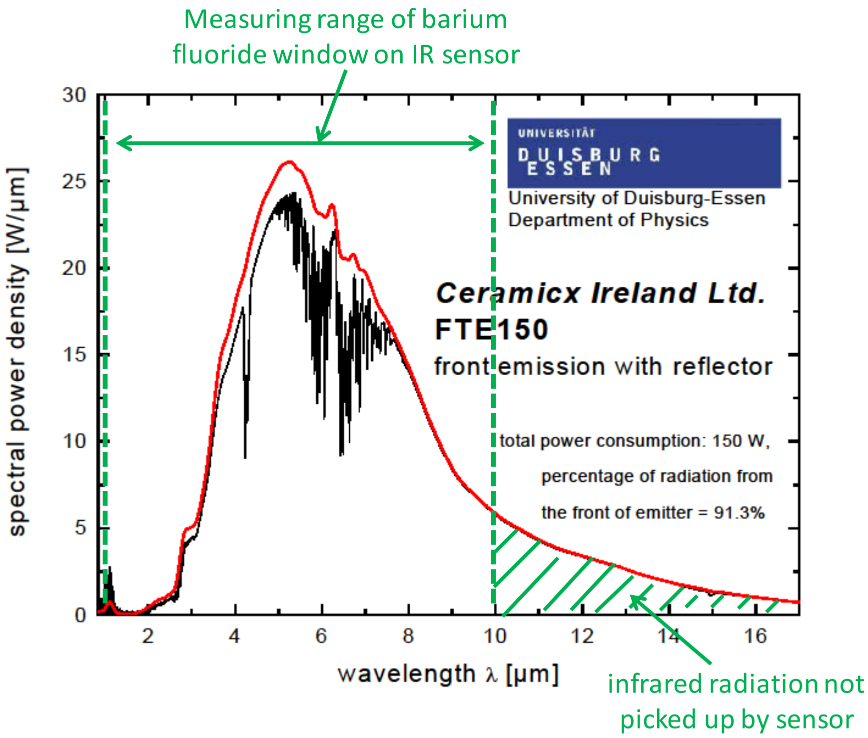

Figure 5: Infrared spectrum of a 150W heater showing region not picked up by IR sensor.

It is interesting to note that the 150 W emitter shows the poorest performance, however although some of the reason may be due to convective loss in heating the surrounding air, another possibility is that the 150 W heater produces a significant portion of its infrared heat above 10 microns as seen in Figure 5. This will not be registered by the infrared sensor due to the transmissive properties of the barium fluoride window which will not transmit infrared radiation above 10µm.

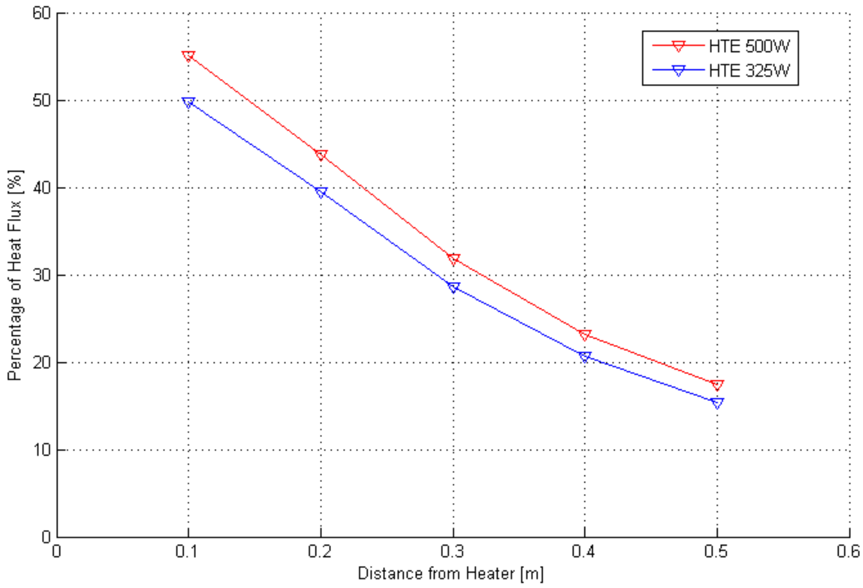

Figure 6: Percentage of input power measured at 500 x 500 mm grid, HTE range

The HTE heaters shown in Figure 6 have similar efficiency levels to the FTE heaters, especially when the power density is taken into account (a 500W HTE has the same power density as a 1000W FTE). The HTE500W returns around 55% while the HTE325W returns around 50%. However this is slightly higher than the 54% and 49% returned by the FTE1000W and FTE650W elements. This may be in part due to the smaller length of the HTE meaning less infrared is emitted beyond the 500mm^2 measuring grid.

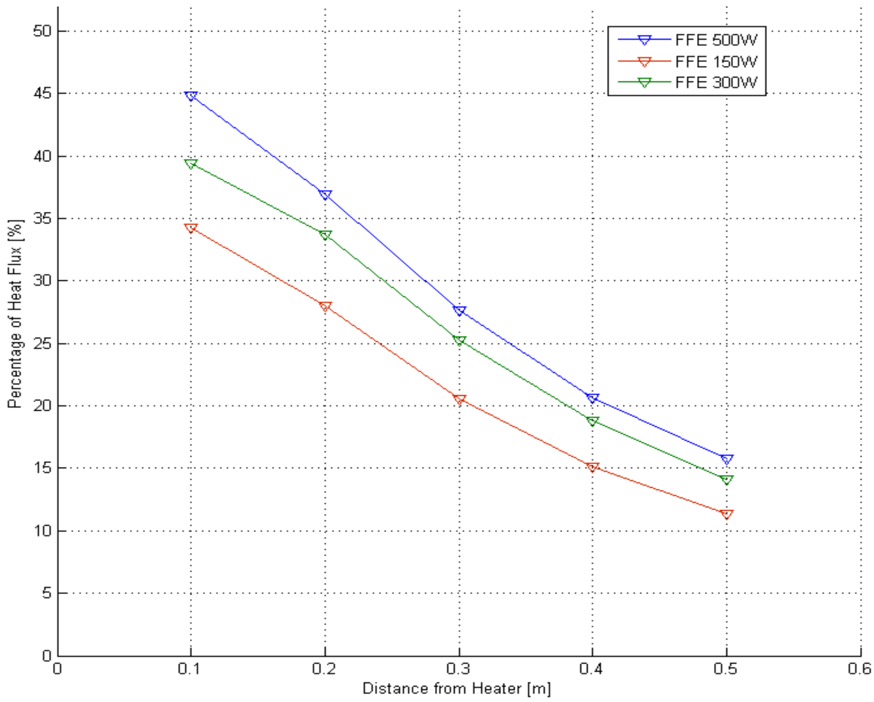

Figure 7: Percentage of input power measured at 500 x 500 mm grid, FFE range

Figure 7 shows the percentage efficiencies of the FFE range tested. The 500W and 300W return a percentage of around 45% and 40% respectively. This compares favourably with the 500w and 300W FTE percentages shown in Figure 4. However the FFE 150W of 34% does not match well with the FTE 150W of 30% as seen in Figure 4. At the moment it is not certain why this is so though the shape of the elements may have an effect, perhaps the flat element radiates a greater portion of its energy to the front and is detected by the sensor, while the trough element may radiate a larger portion outside the range of the 500 by 500mm measuring grid at 100mm.

FFEH, HFEH and FTE

In Figure 8 the hollow elements both FFEH and HFEH have higher maxima than their FTE counterparts. For the FFEH element, maximum heat flux values range from 0.25 W/cm^2 at 250W to 1.37 W/cm^2 at 1000W (this heater is currently in development). This is approximately a 20% higher heat flux than that emitted by the flat and trough elements at 100mm.

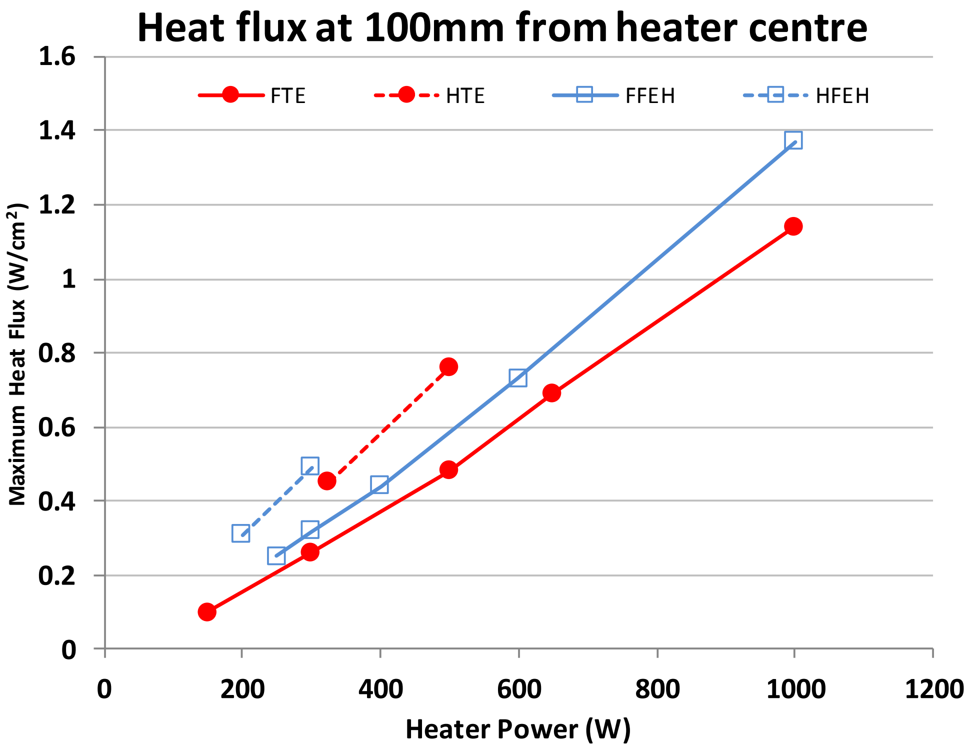

Figure 8: Maximum heat flux values at 100mm for FFEH, HFEH, FTE and HTE (W/cm^2)

Despite no overlap between the wattage range of HTE and HFEH elements tested, by extrapolation of the curves, it is reasonable to conclude that a similar 20% improvement also exists. Similarly the half size hollow elements for a given wattage exhibit higher maximum heat flux values than the equivalent wattage full size element. As before, it must be remembered that for a given wattage, the power density of a half size element is double the full size element thus explaining this increase.

POINT TO NOTE: At 100mm, a hollow FFEH element will give around 20% higher maximum heat flux than the flat and trough FFE/FTE elements.

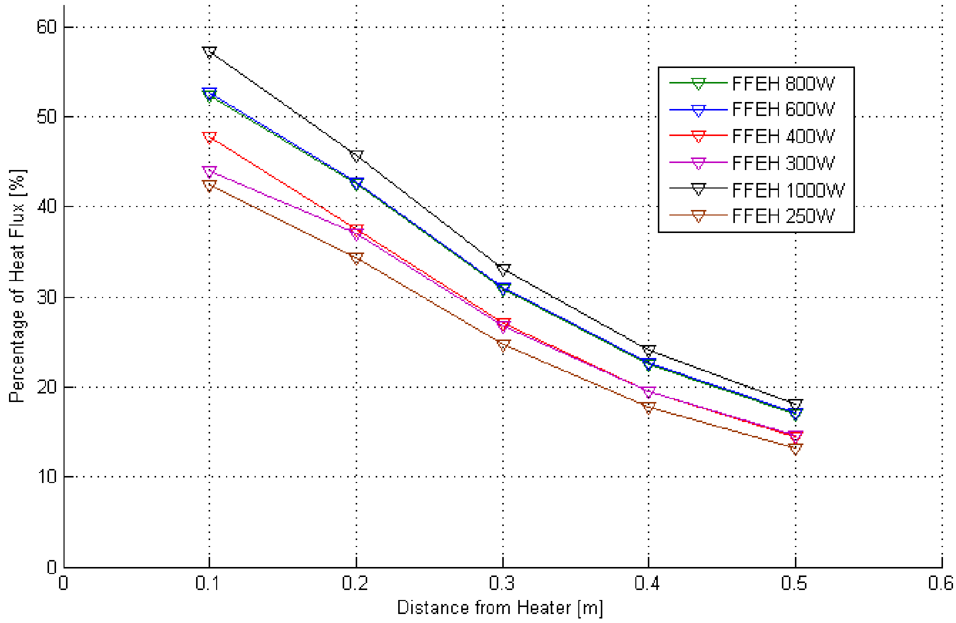

Figure 9: Percentage of input power measured at 500 x 500 mm grid, FFEH range

Figure 9 shows the percentage values for the FFEH range of elements. The largest percentage of 57% is returned from the FFEH 1000W. This decreases progressively to around 18% with distance from the element. FFEH 800W and 600W are next at around 53% each, again decreasing to around 17% with distance. As the element wattage decreases, so too do the general trends of other FFEH elements as can be seen in Figure 9.

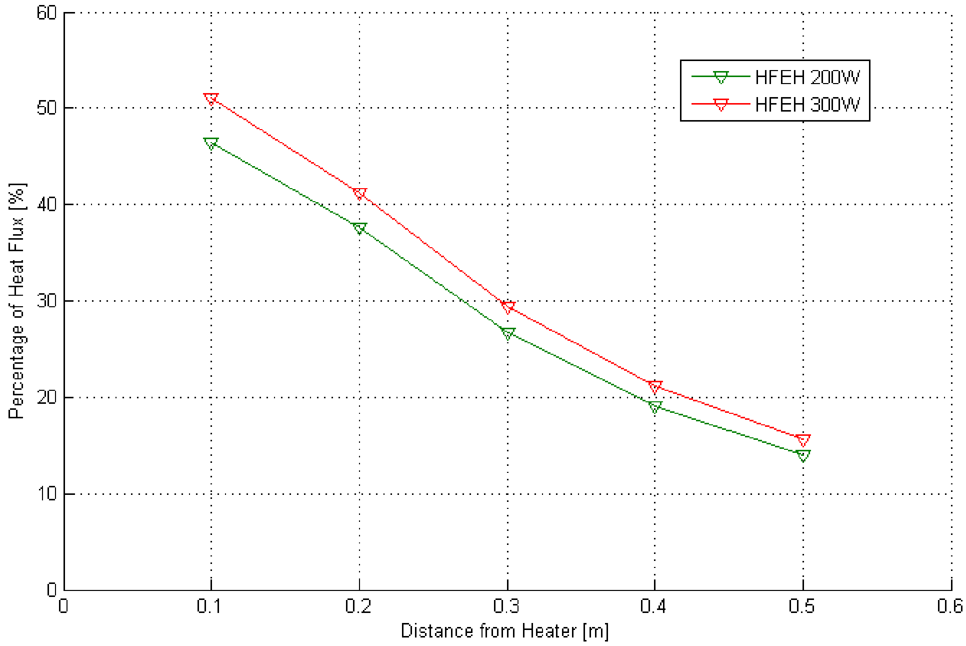

Figure 10: Percentage of input power measured at 500 x 500 mm grid, HFEH range

The percentage values for the HFEH elements tested are shown in Figure 10. The HFEH 300W returns around 51% at 100mm decreasing with distance to around 15% at 500mm.

The HFEH 200W is slightly lower at around 46% at 100mm. For a given power density, the half size HFEH elements return roughly 2% less than their full size FFE counterparts (53% and 48%) for both elements tested (see Figure 9). This is different from the FTE and HTE where the HTE elements returned around 1% higher than the FTE.

FQE HQE and FFEH

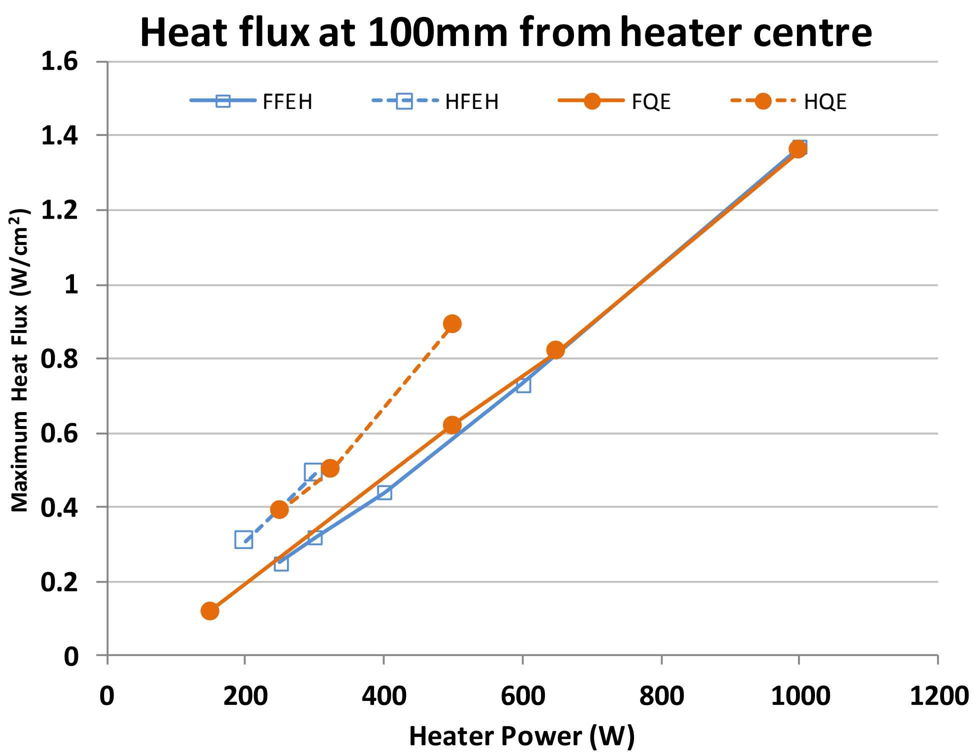

Figure 11: Maximum heat flux values at 100mm for FQE and HQE compared to FFEH and HFEH (W/cm^2)

In Figure 11 the quartz cassette elements are compared to hollow ceramic elements. It is noticed that the performance levels of FQE and FFEH are broadly equivalent and it is safe to conclude that maximum heat flux levels for a quartz and hollow element are equivalent. There is only a small overlap in the element wattages of HQE and HFEH elements tested, but extrapolation of the trends also support the equivalent performance of these elements.

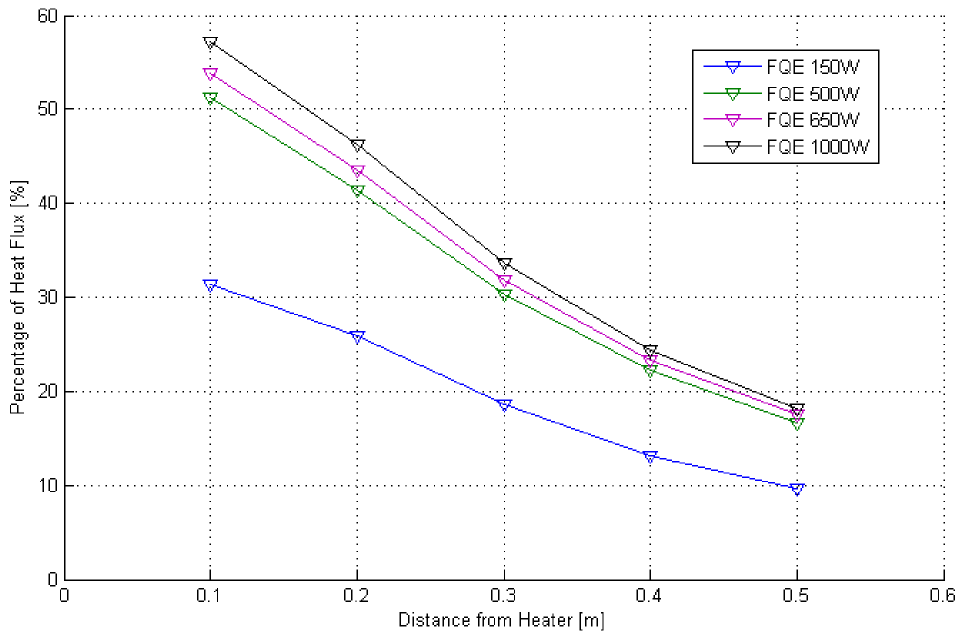

Figure 12: Percentage of input power measured at 500 x 500 mm grid, FQE range

Figure 12 shows the percentage values for the FQE range of elements. The largest percentage of 57% is returned from the FQE 1000W. This decreases progressively to around 18% with distance from the element. FQE 650W and 500W are next at around 54% and 51% respectively, again decreasing to around 16-17% with distance. As the element wattage decreases, so too do the general trends of other FFEH elements. The FQE 150W appears to return a very low value of only around 31% at a distance of 100mm, with 10% of the input power being detected at a distance of 500mm. The reason for this may be similar to the FTE150W as shown earlier in Figure 5. This may be due to the infrared emission of the FQE 150W element, where any emission above 10 microns will not be detected by the sensor. No infrared emission graph is currently available for the FQE150W to check this.

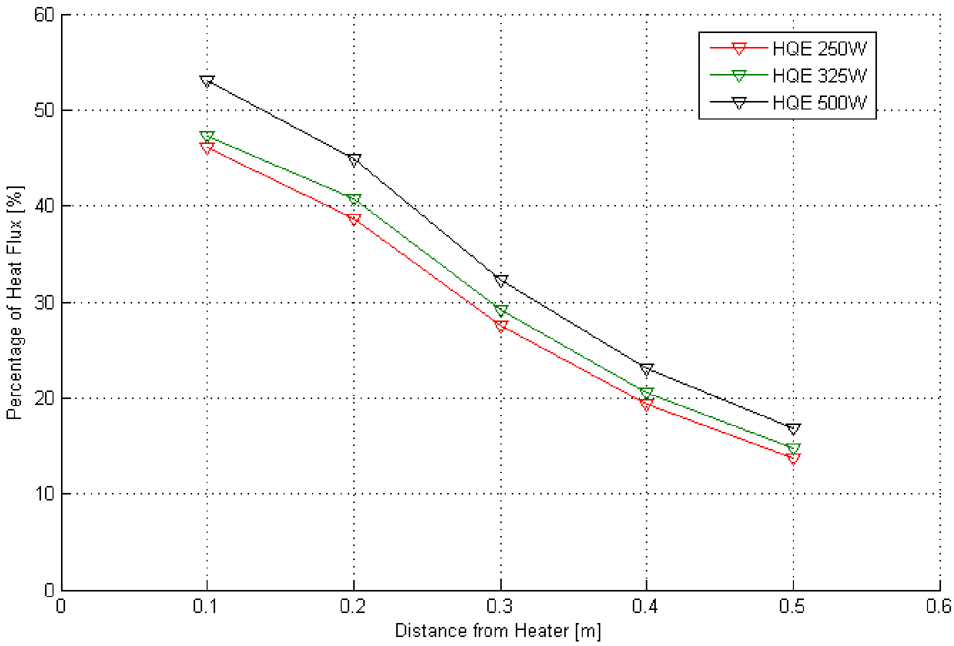

Figure 13: Percentage of input power measured at 500 x 500 mm grid, HQE range

The percentage values for the HQE element tested are shown in Figure 13. For a given power density, the half size quartz elements perform in all cases 3-4% lower than their full size counterparts (see Figure 12and Figure 13). One interesting observation is that when similar comparisons were made between FTE and HTE, the half size elements were actually higher by around 1% percent (see Figure 4 and Figure 6). It is not known if these differences are characteristics of the ceramic and quartz elements, or if it is a testing issue, where the 25mm step size during IR measurement could be too coarse for half size elements, thus causing slight variations in readings.

POINT TO NOTE: At 100mm, a quartz element will give the same maximum heat flux as a hollow element.

SFSE SFEH and FFEH

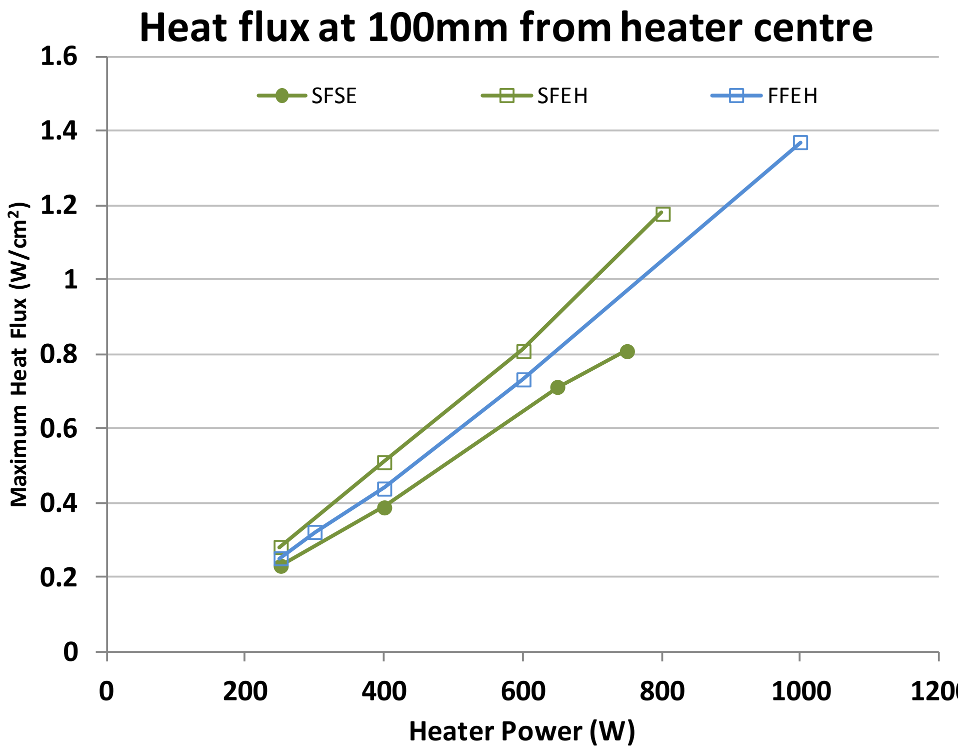

Figure 14: Maximum heat flux values at 100mm for SFSE and SFEH compared to FFEH (W/cm²)

In Figure 14 the maximum heat flux values for the square elements are compared. The plain flat SFSE element ranges from 0.23 at 250W up to 0.81 at 750W. However the hollow SFEH elements range from 0.28 at 250W up to 1.18 at 800W. In general, the hollow element heat flux values exceed the solid element values by up to 30%. This is a greater difference when compared to the FFEH and FTE difference of 20%. This may be explainable by the ratio of front surface area emissions to side perimeter emissions. The front surface area of an FTE or FFE element is $0.1470m^2$ while its perimeter is 0.61m. The surface area of the SFEH element is similar at $0.01488m^2$ however its perimeter is much smaller at 0.488m. This means that a smaller perimeter of the square element can emit less radiation in comparison to the full size elements, therefore more is available for frontal transmission.

It is not known if this difference would be apparent in an array situation as the effective perimeter is then going to be the outer dimensions of the platen, regardless of the type of element used.

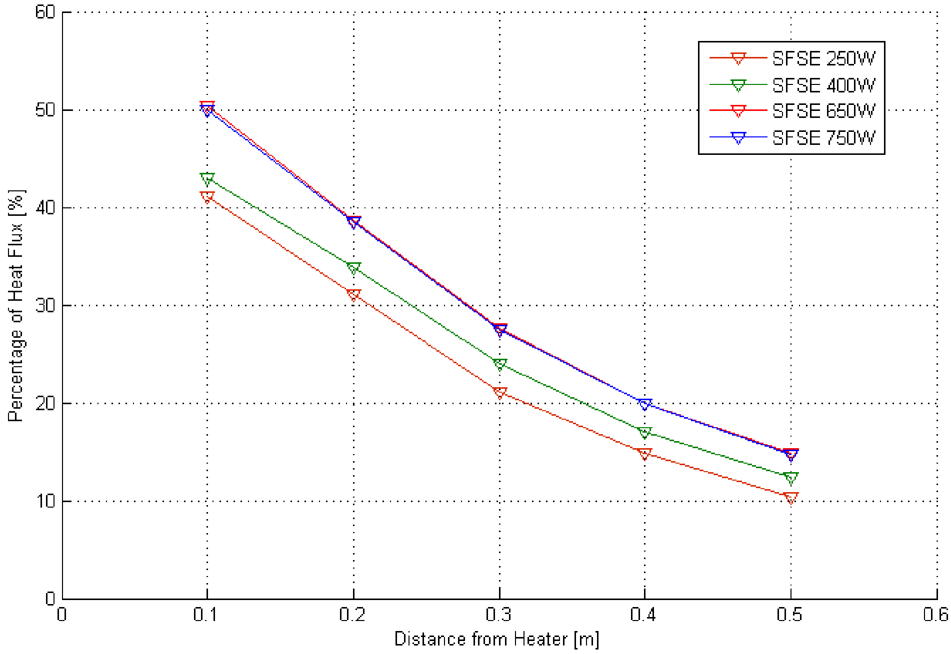

Figure 15: Percentage of input power measured at 500 x 500 mm grid, SFSE range

The percentage values for the SFSE element tested are shown in Figure 15. The largest percentage of 50% is returned from the SFSE 750 and 650W. This decreases progressively to around 15% with distance from the element. As element wattage decreases, so do the trends of other SFSE elements. SFSE 400W and 250W return 43% and 41% at 100mm respectively, again this decreases to around 12-10% with distance up to 500mm from the element.

POINT TO NOTE: THE SFEH gives a higher maximum heat flux than the SFSE by about 30%.

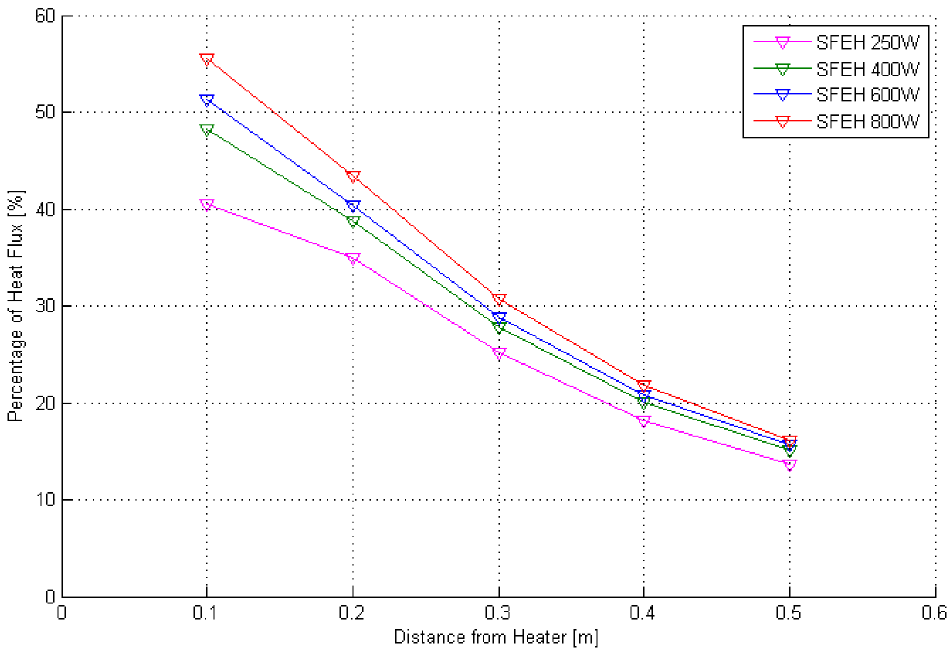

Figure 16: Percentage of input power measured at 500 x 500 mm grid, SFEH range

The percentage values for the SFEH element tested are shown in Figure 16. The largest percentage of 56% is returned from the SFEH 800W. This is around 6% higher than the 750W SFSE element. As with other elements, this decreases progressively to around 16% at 500mm from the element. As element wattage decreases, so do the trends of other SFSE elements. SFSE 400W and 250W return 43% and 41% at 100mm respectively, again this decreases to around 12-10% with distance up to 500mm from the element. However, the SFEH modules return a higher percentage than the SFSE modules. This is comparable in the 400W powers, where the SFEH return 43%, while the SFEH returns around 48%.

Individual Graphs of elements tested.

All graphs of elements tested are now presented. Both heat flux graphs and percentage graphs are shown. Note; for the purposes of clarity, the heat flux colour bar legend is changed to suit the maximum heat flux recorded for each element. This means the full colour spectrum is available to illustrate the heat flux profile. For all standard rectangular elements (245 x 60mm) the heat flux profiles are semi elliptical in the horizontal direction and hemi-circular in the vertical direction. No differences are noticed between element types such as quartz, or hollow.

FTE

Table 2: FTE Family, maximum heat flux measured (W/cm² at 100mm)

FTE	150W	300W	500W	650W	1000W
	0.1	0.26	0.48	0.69	1.14

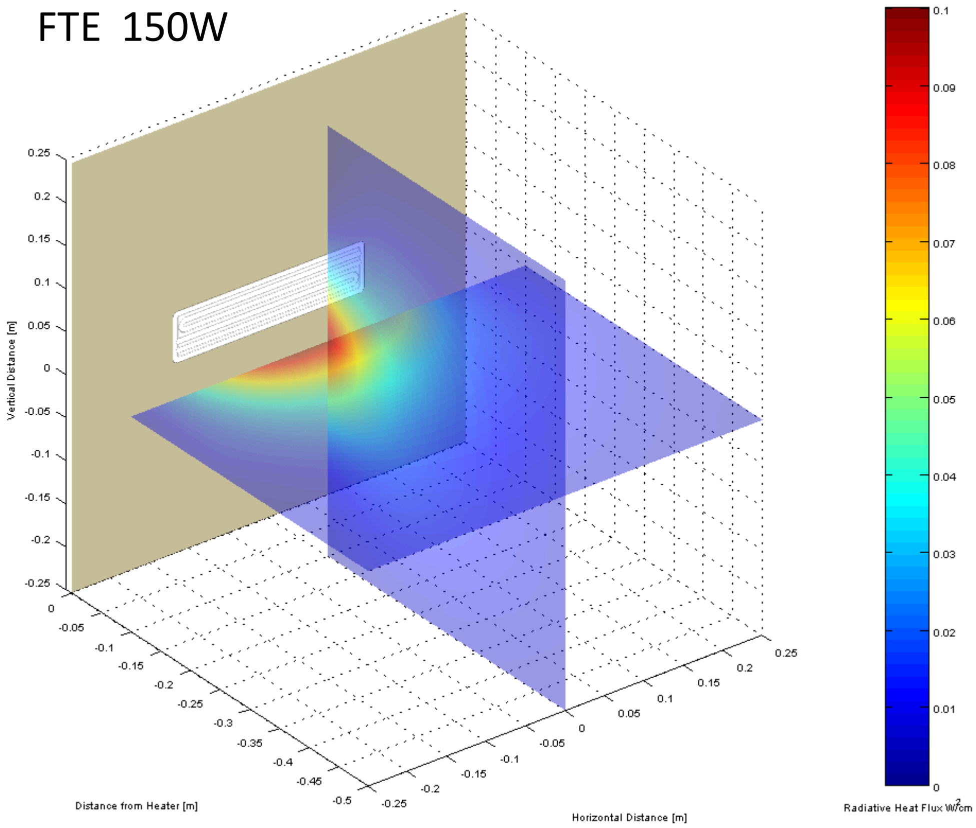

Figure 17: FTE 150W 3D heat flux profile, max heat flux @ 100mm ~0.10W/cm²

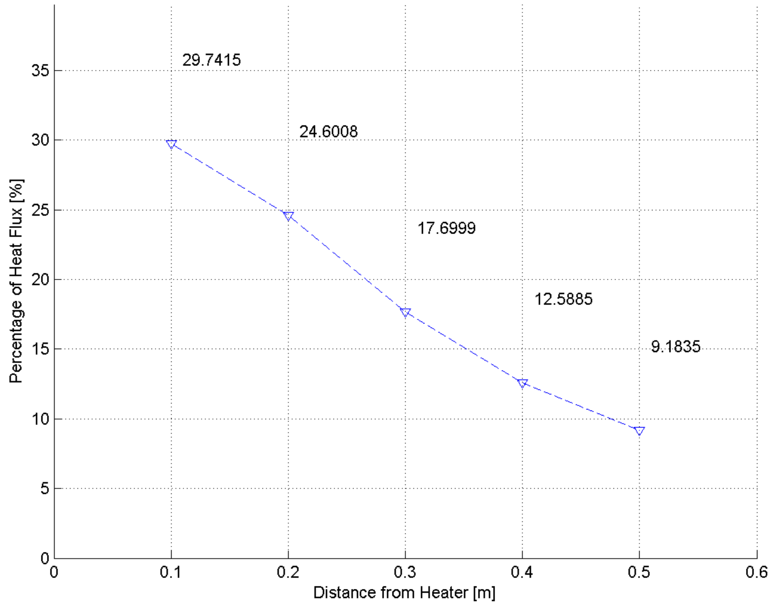

Figure 18: Percentage of input power measured at 500 x 500 mm grid, FTE 150W

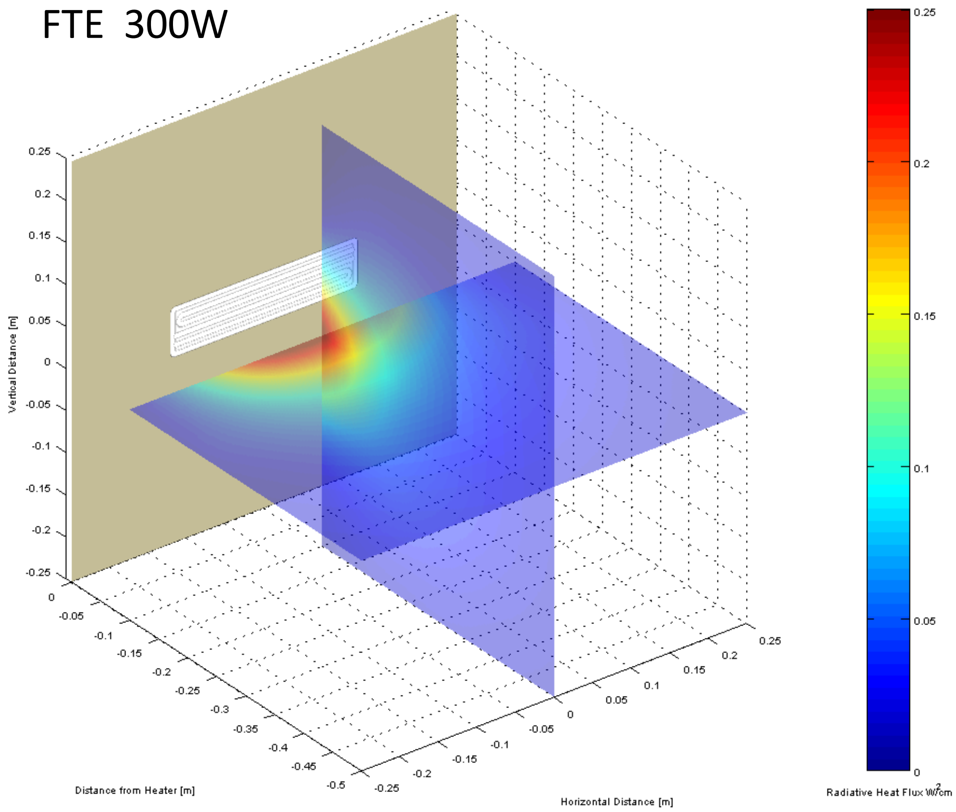

Figure 19: FTE 300W 3D heat flux profile, max heat flux @ 100mm ~0.26W/cm²

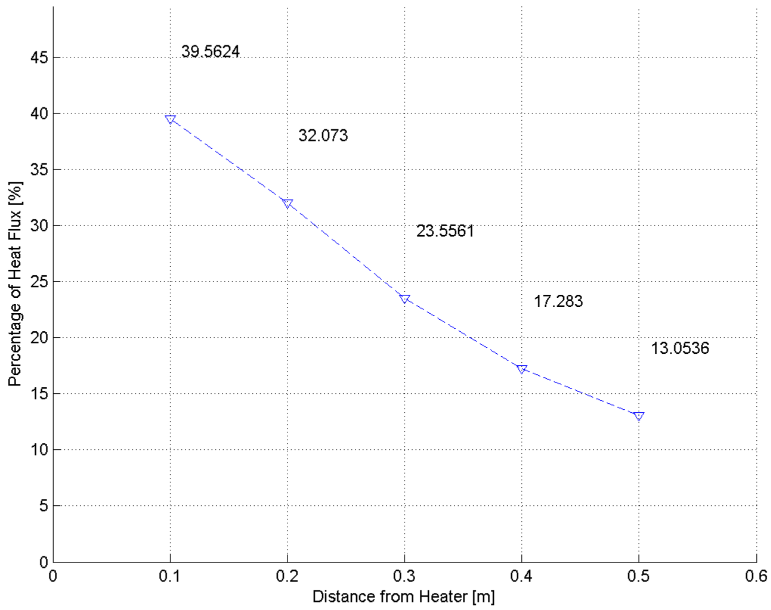

Figure 20: Percentage of input power measured at 500 x 500 mm grid, FTE 300W

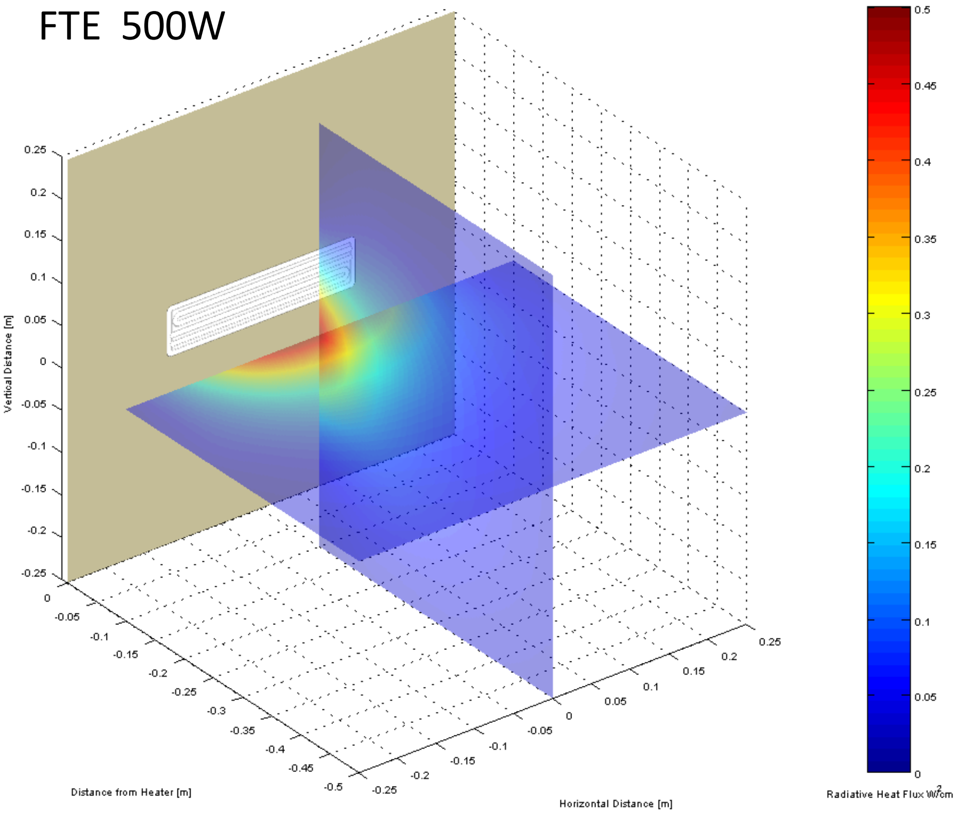

Figure 21: FTE 500W 3D heat flux profile, max heat flux @ 100mm ~0.48W/cm²

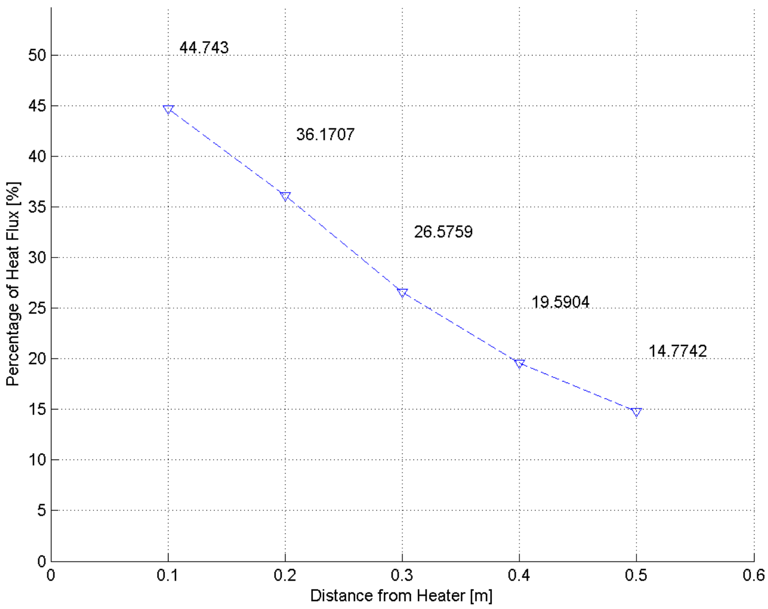

Figure 22: Percentage of input power measured at 500 x 500 mm grid, FTE 500W

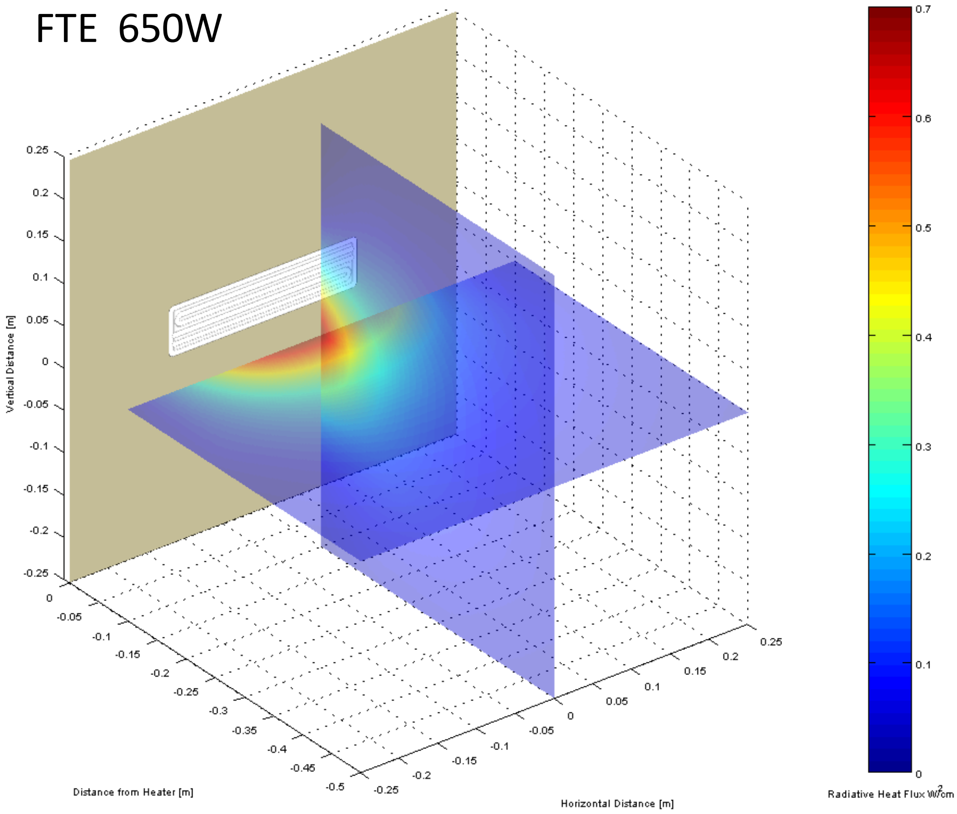

Figure 23: FTE 650W 3D heat flux profile, max heat flux @ 100mm ~0.69W/cm²

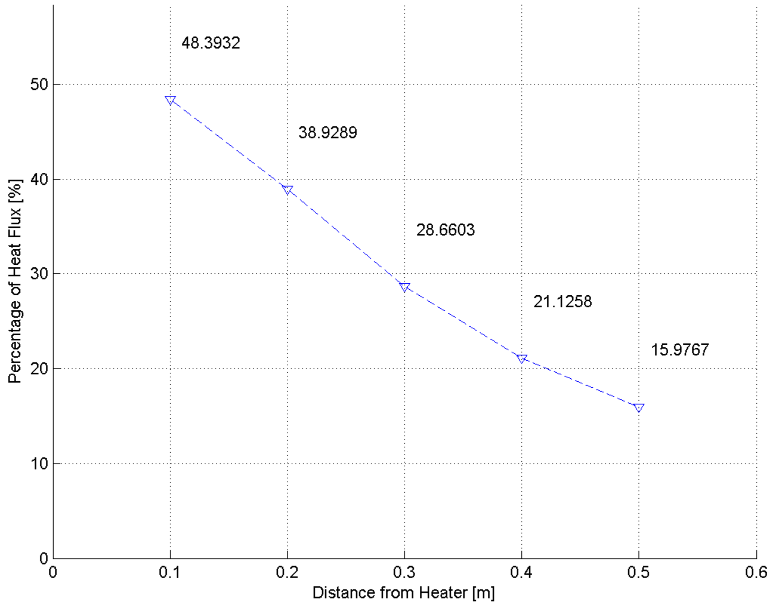

Figure 24: Percentage of input power measured at 500 x 500 mm grid, FTE 650W

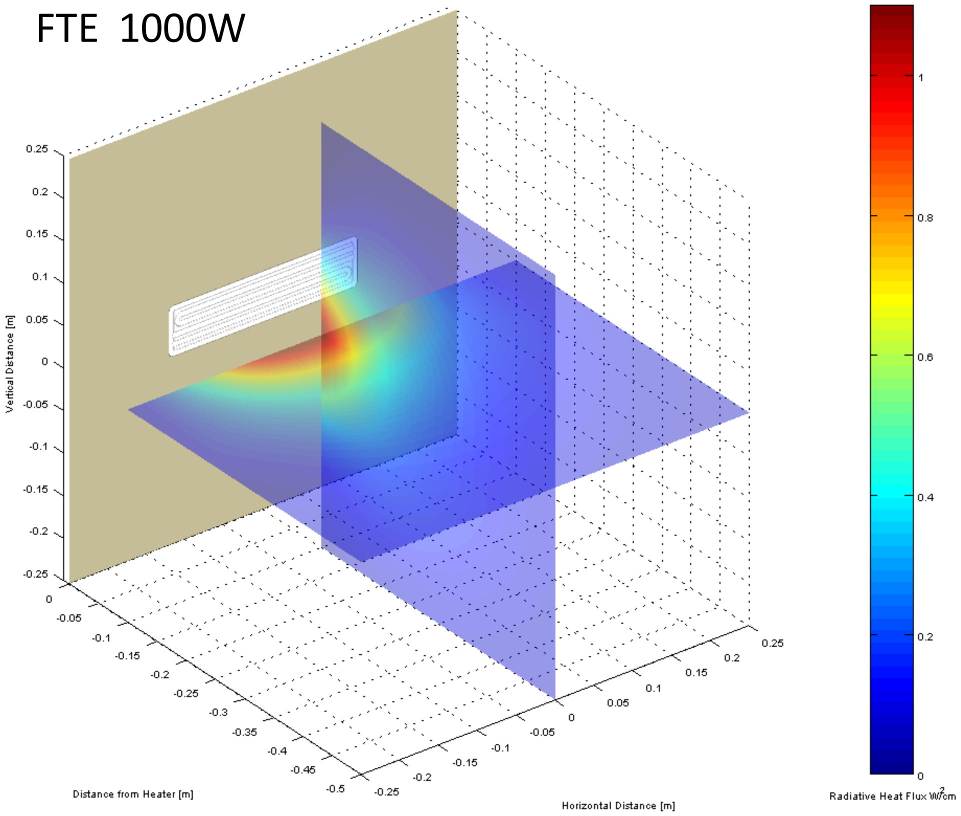

Figure 25: FTE 1000W 3D heat flux profile, max heat flux @ 100mm ~1.14W/cm²

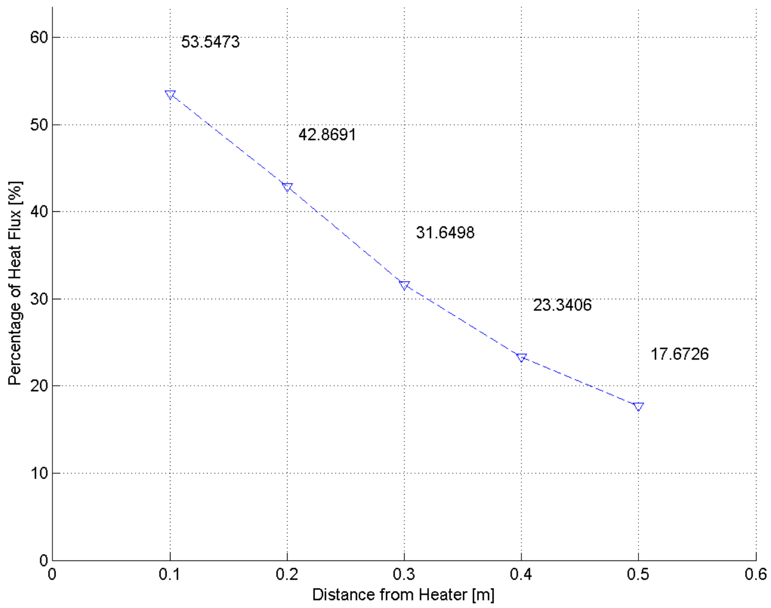

Figure 26: Percentage of input power measured at 500 x 500 mm grid, FTE 1000W

HTE

Table 3: HTE Family, maximum heat flux measured (W/cm² at 100mm)

HTE	325W	500W
	0.45	0.76

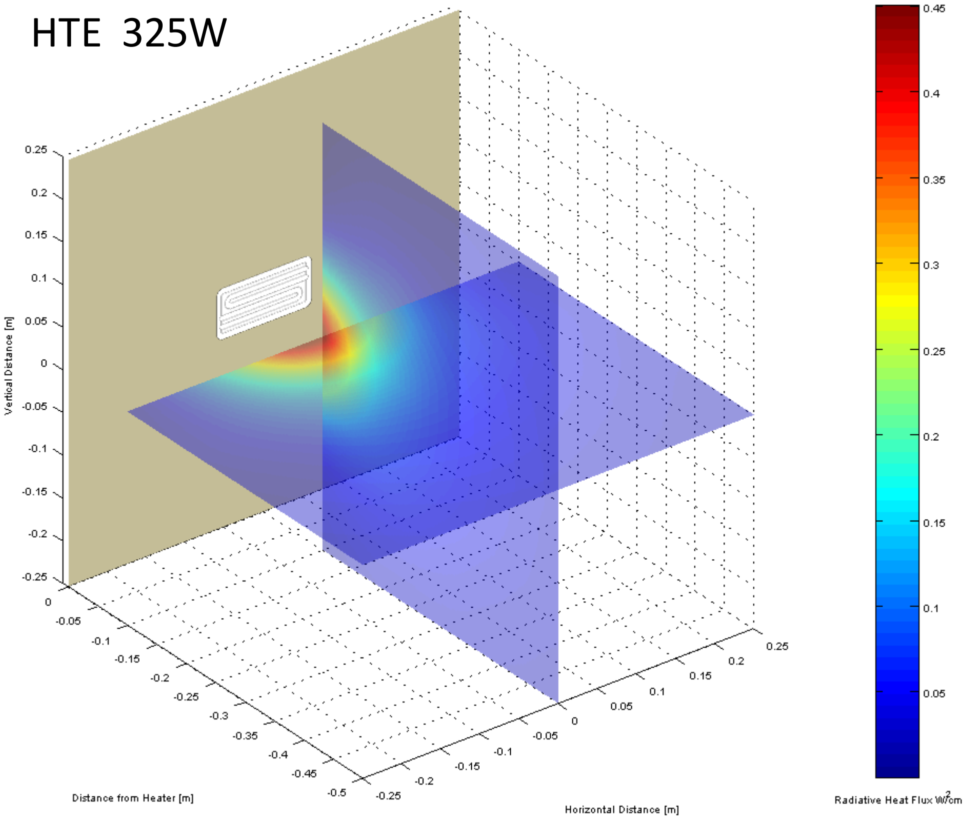

Figure 27: HTE 325W 3D heat flux profile, max heat flux @ 100mm ~0.45W/cm²

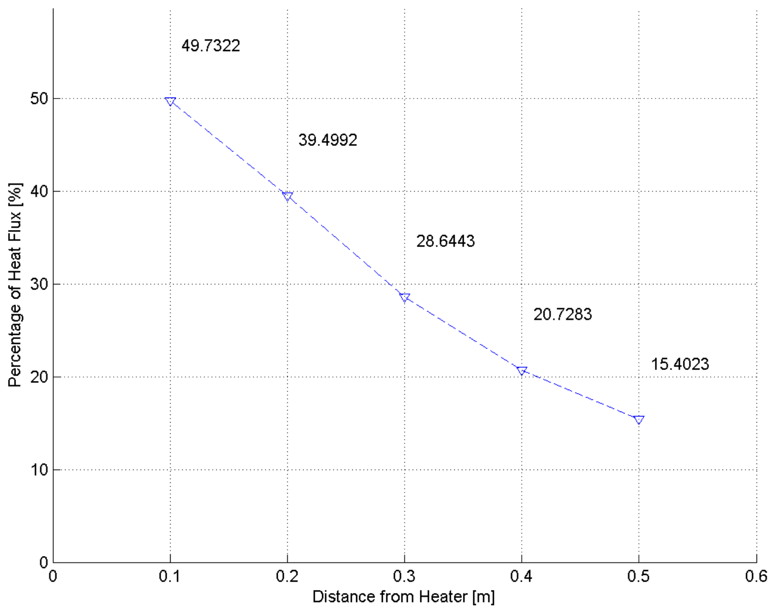

Figure 28: Percentage of input power measured at 500 x 500 mm grid, HTE 325W

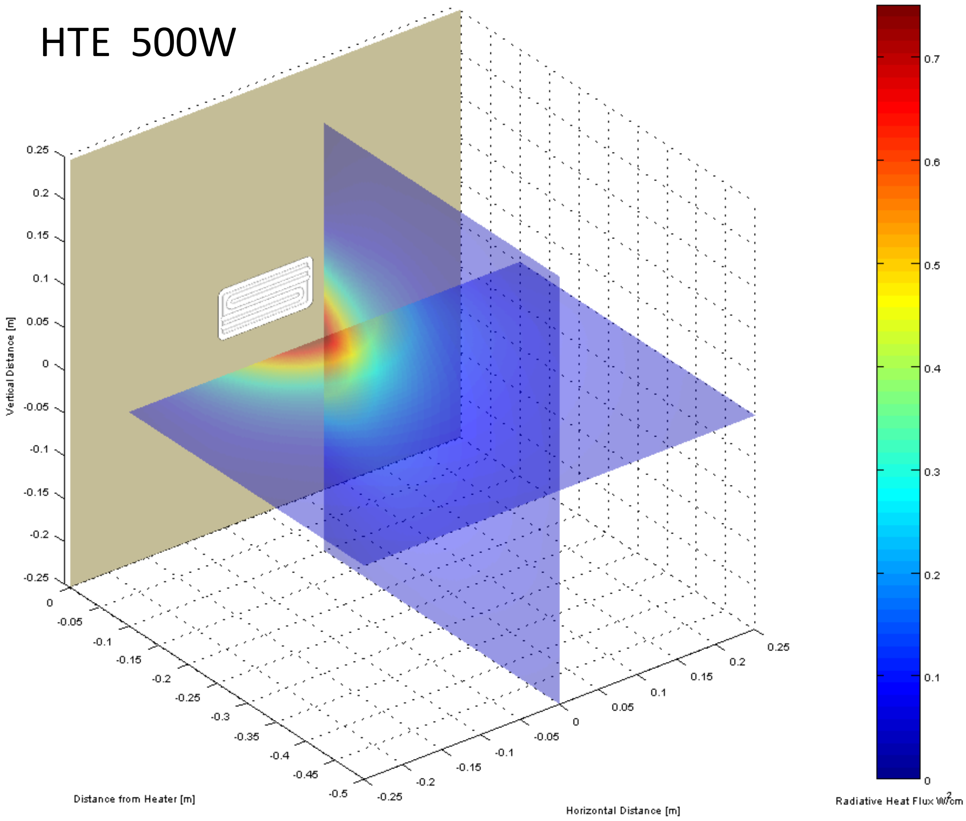

Figure 29: HTE 500W 3D heat flux profile, max heat flux @ 100mm ~0.76W/cm²

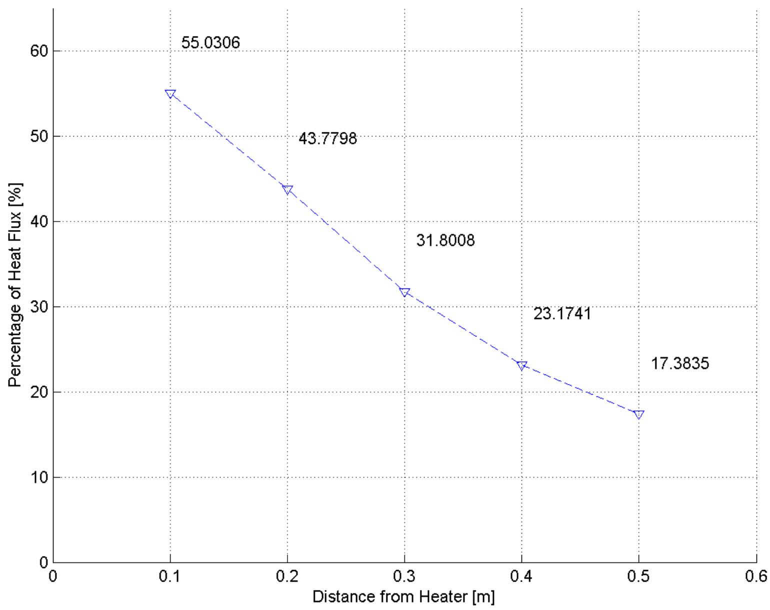

Figure 30: Percentage of input power measured at 500 x 500 mm grid, HTE 500W

FFEH

Table 4: FFEH family, maximum heat flux measured (W/cm² at 100mm)

FFEH	250W	300W	400W	600W	1000W	(1000W European)
	0.25	0.32	0.44	0.73	1.37	1.37

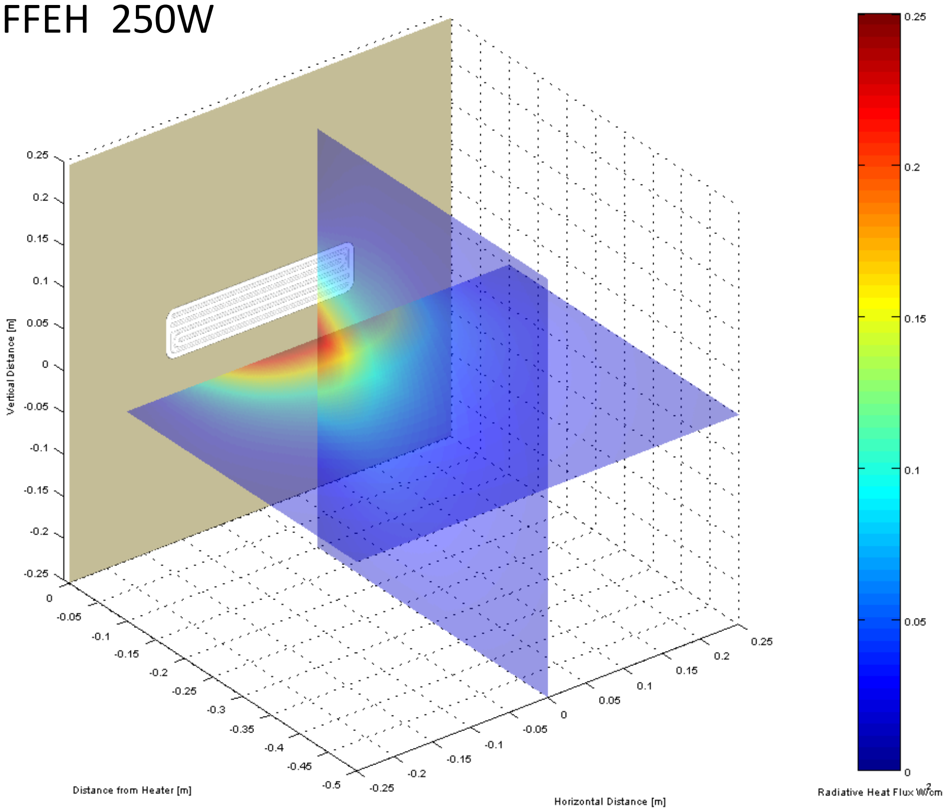

Figure 31: FFEH 250W 3D heat flux profile, max heat flux @100mm ~0.25W/cm²

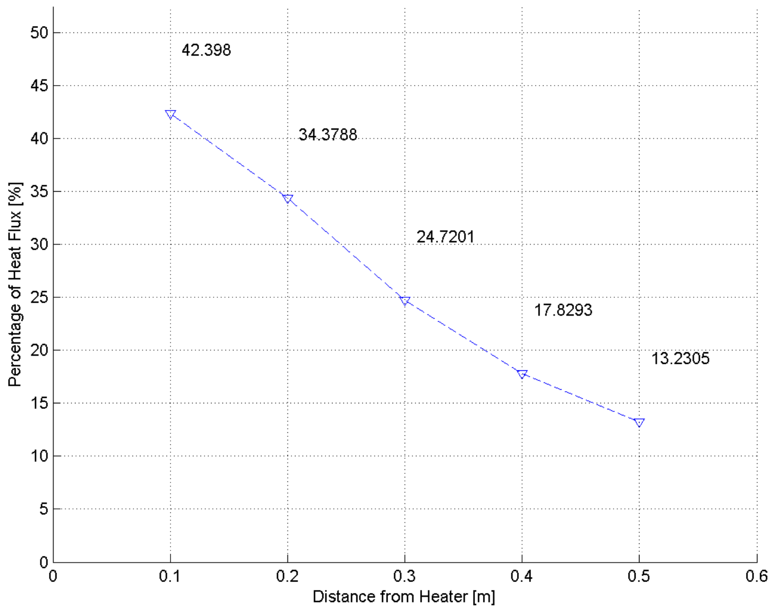

Figure 32: Percentage of input power measured at 500 x 500 mm grid, FFEH 250W

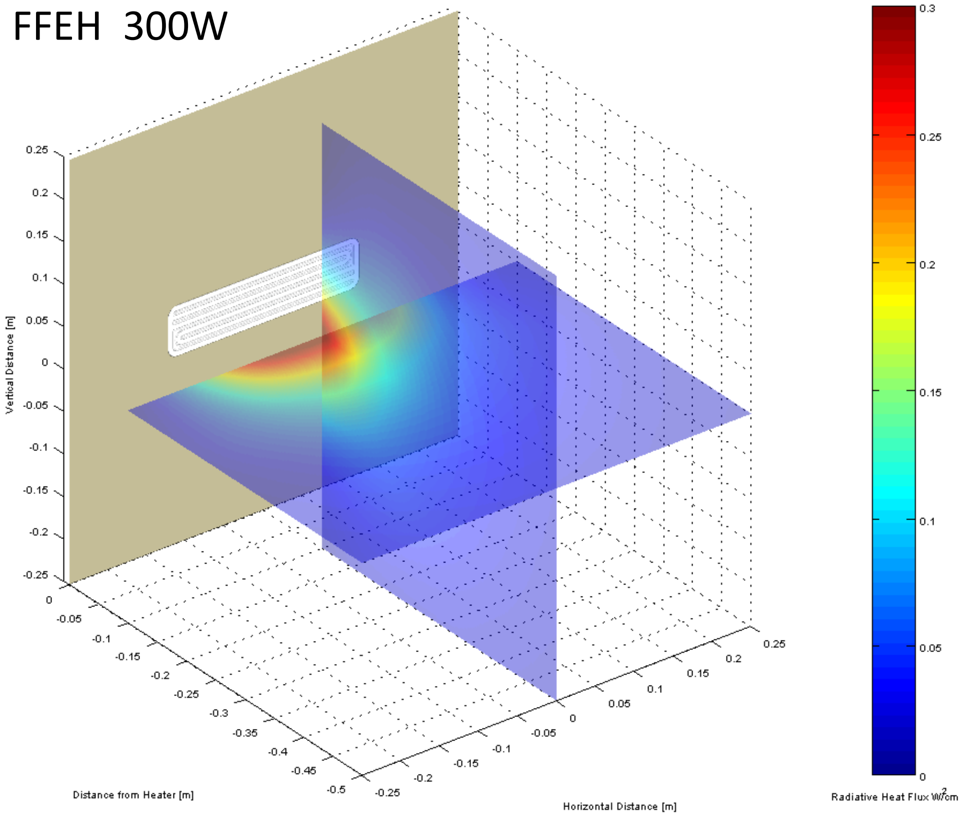

Figure 33: FFEH 300W 3D heat flux profile, max heat flux @100mm ~0.32W/cm²

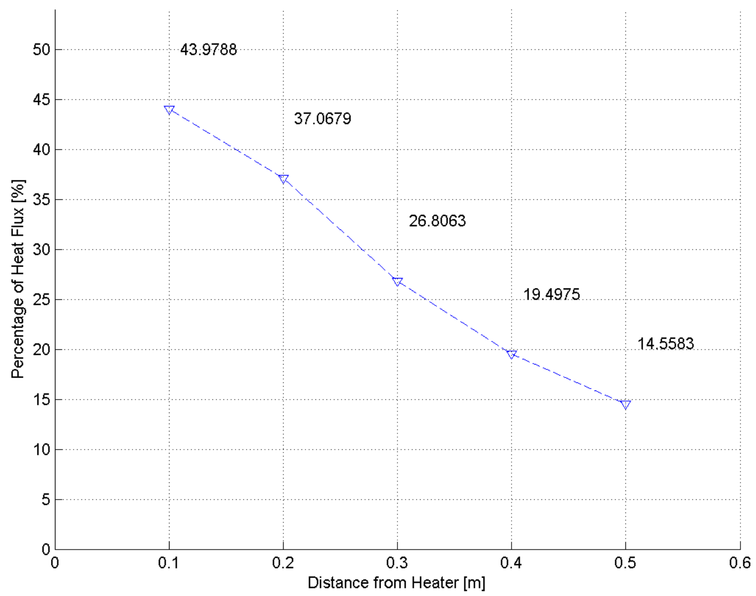

Figure 34: Percentage of input power measured at 500 x 500 mm grid, FFEH 300W

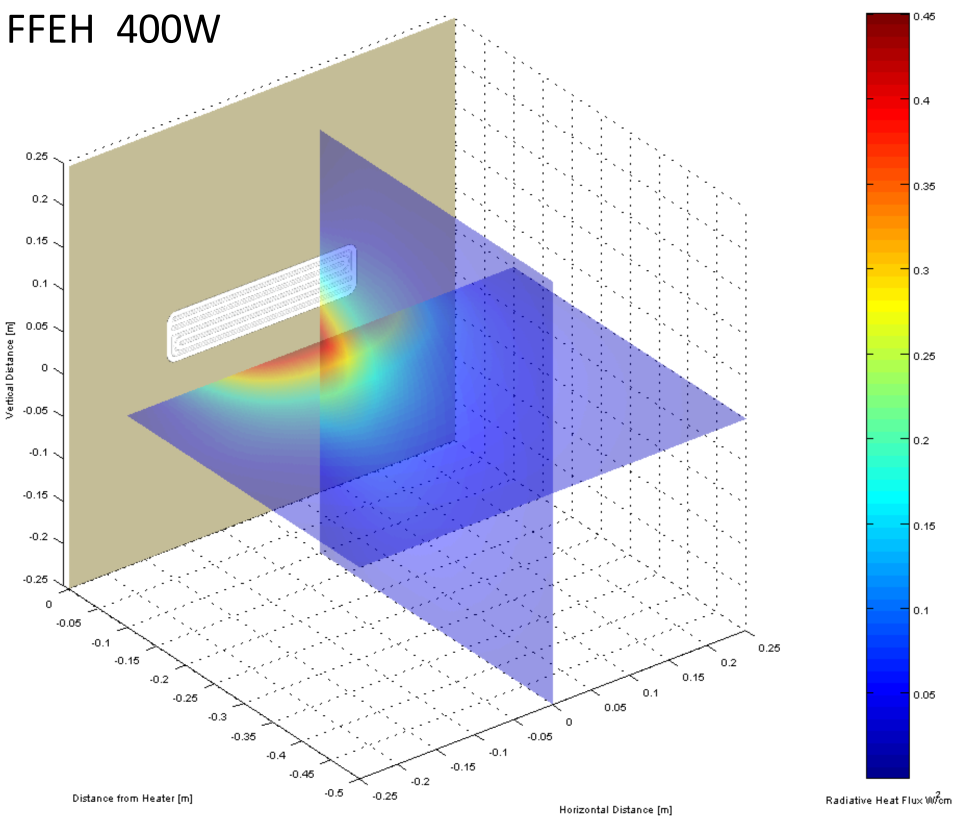

Figure 35: FFEH 400W 3D heat flux profile, max heat flux @100mm ~0.44W/cm²

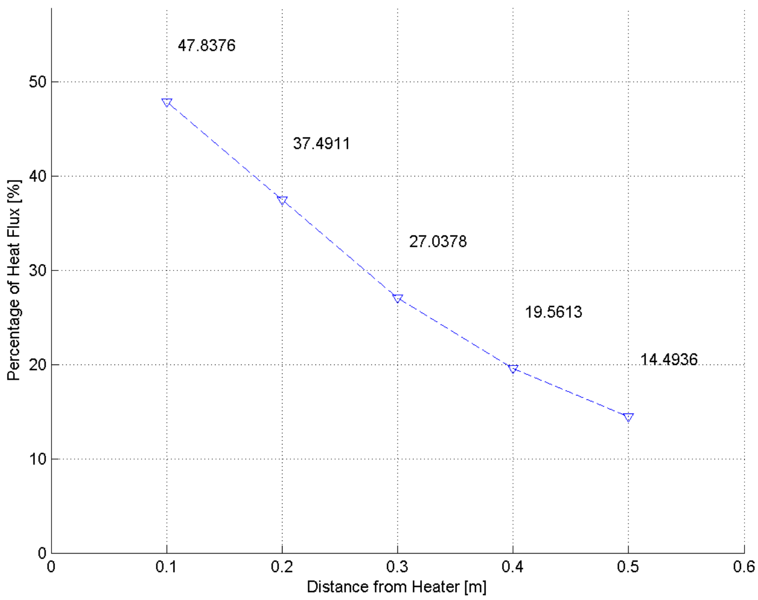

Figure 36: Percentage of input power measured at 500 x 500 mm grid, FFEH 400W

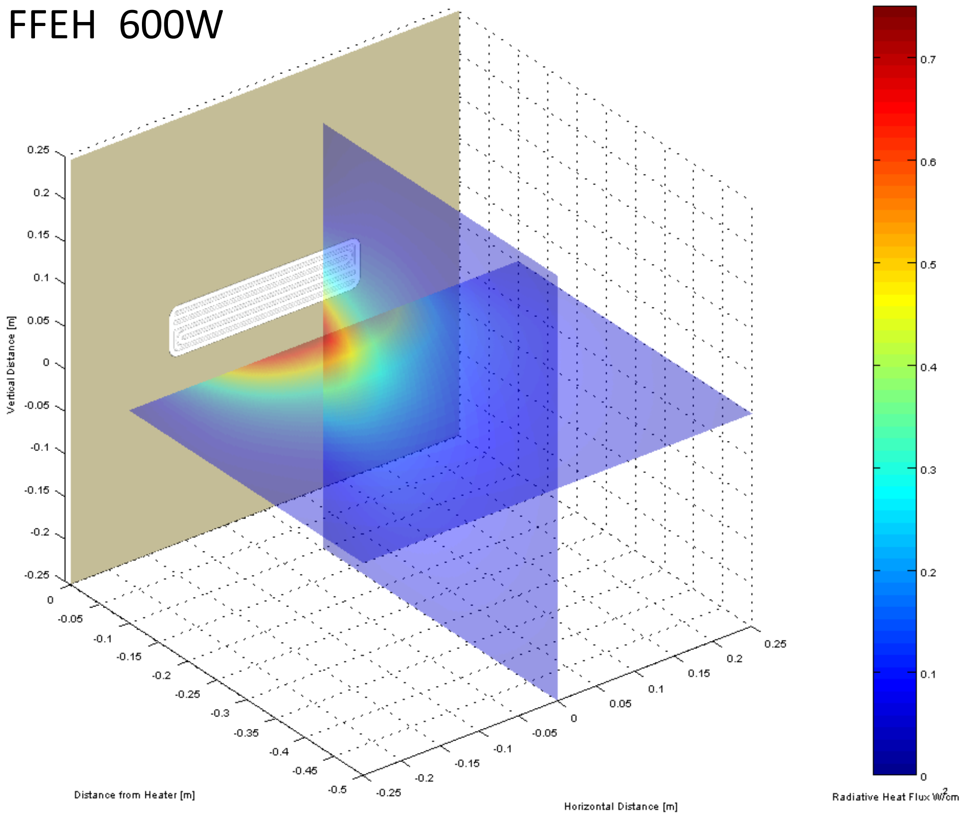

Figure 37: FFEH 600W 3D heat flux profile, max heat flux @100mm ~0.73W/cm²

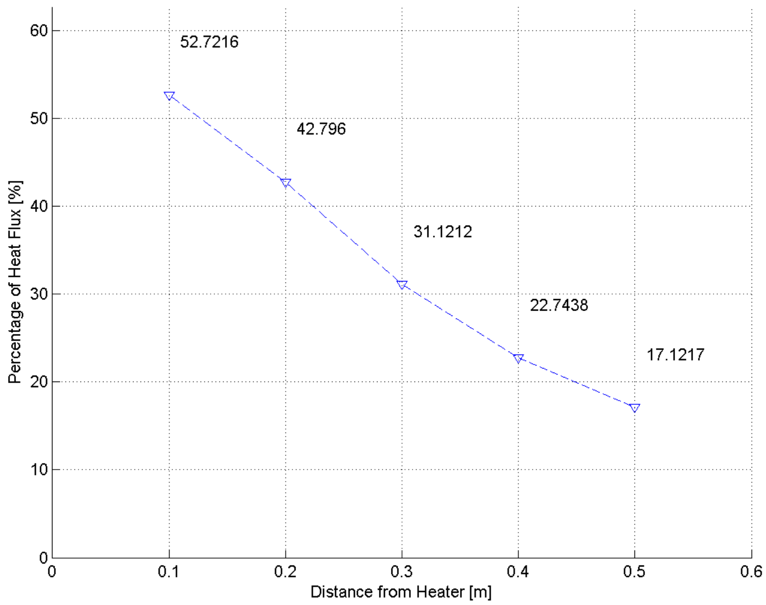

Figure 38: Percentage of input power measured at 500 x 500 mm grid, FFEH 600W

HFEH

Table 5: HFEH Family, maximum heat flux measured (W/cm² at 100mm)

HFEH	200W	300W
	0.31	0.49

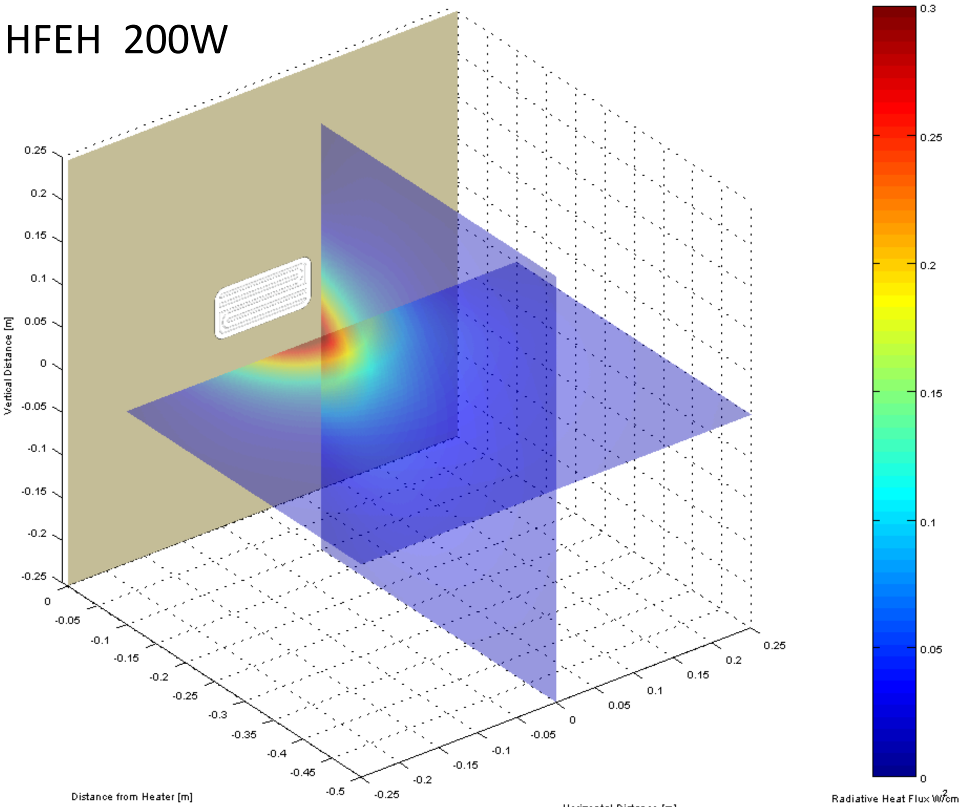

Figure 39: HFEH 200W 3D heat flux profile, max heat flux @ 100mm ~0.31W/cm²

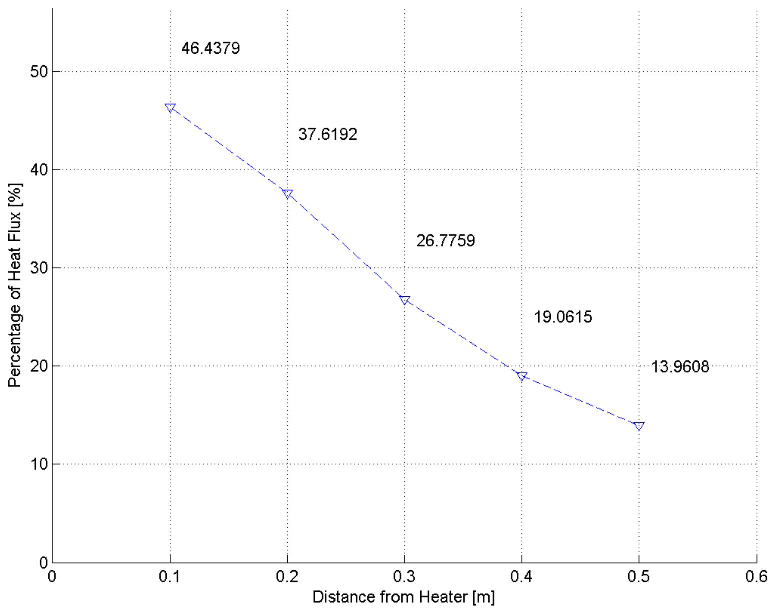

Figure 40: Percentage of input power measured at 500 x 500 mm grid, HFEH 200W

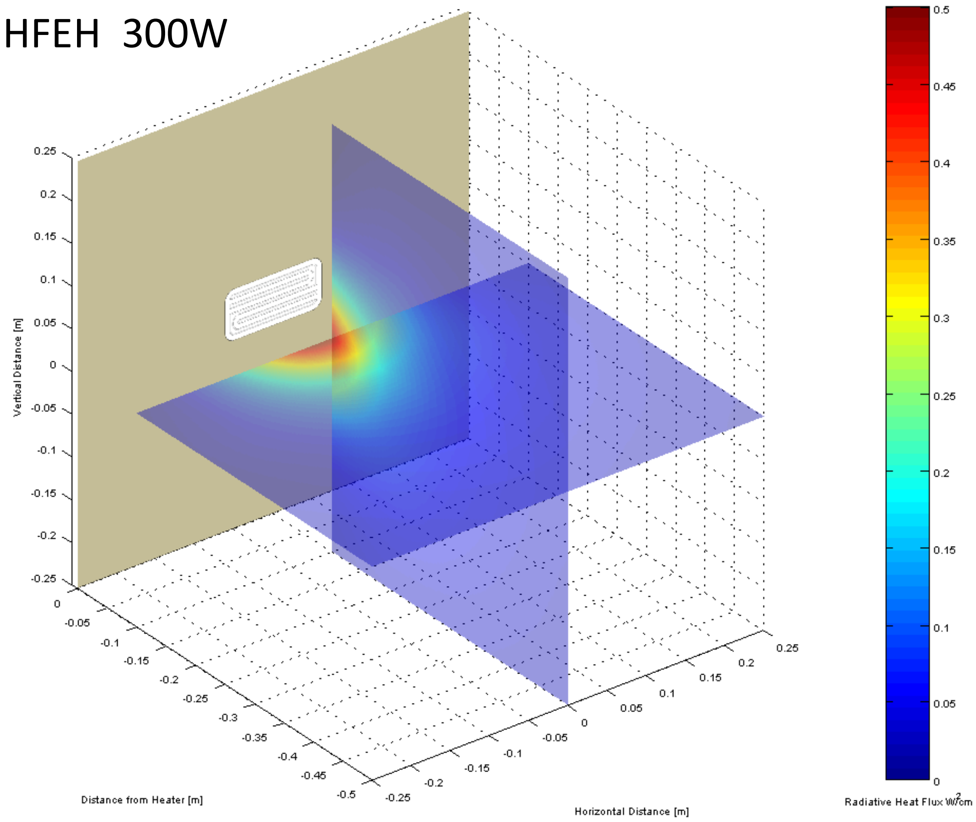

Figure 41: HFEH 300W 3D heat flux profile, max heat flux @ 100mm ~0.49W/cm²

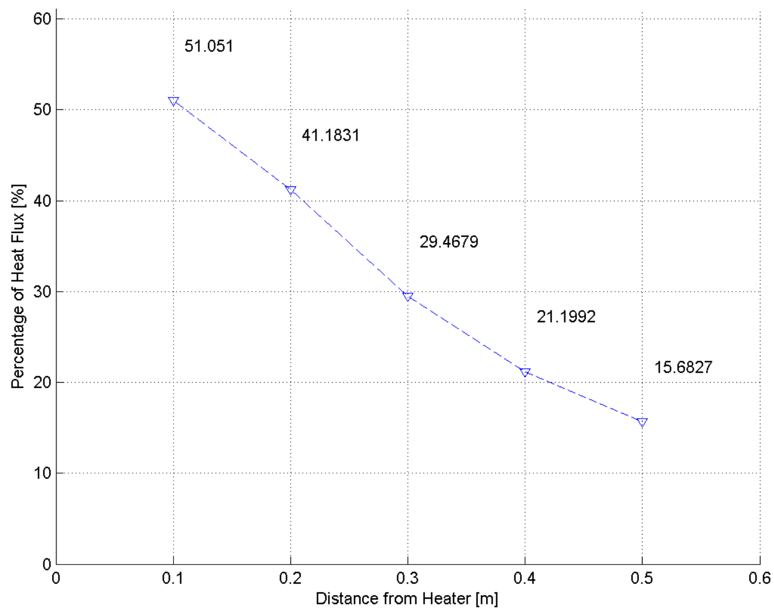

Figure 42: Percentage of input power measured at 500 x 500 mm grid, HFEH 300W

FFE

Table 6: FFE family, maximum heat flux measured (W/cm² at 100mm)

FFE	150W	300W	500W
	0.1	0.25	0.47

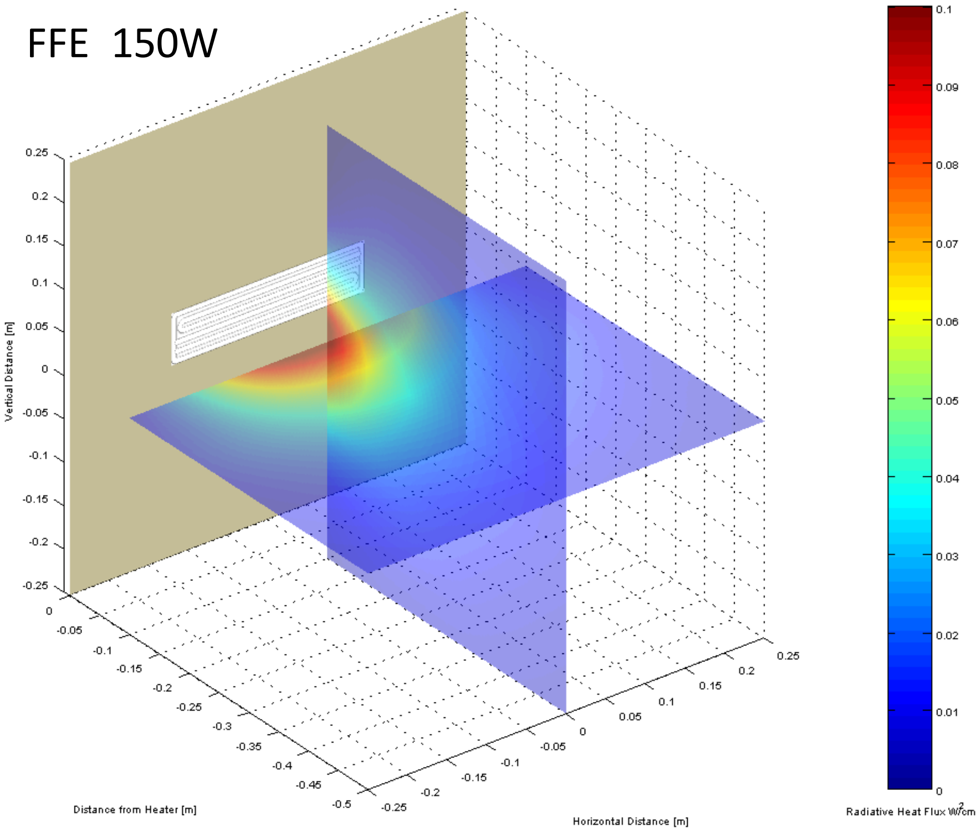

Figure 43: FFE 150W 3D heat flux profile, max heat flux @ 100mm ~0.10W/cm²

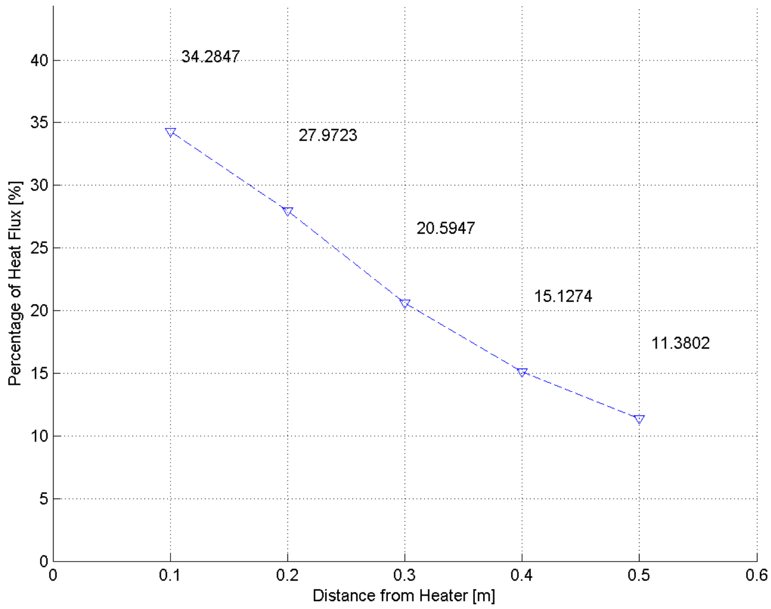

Figure 44: Percentage of input power measured at 500 x 500 mm grid, FFE 150W

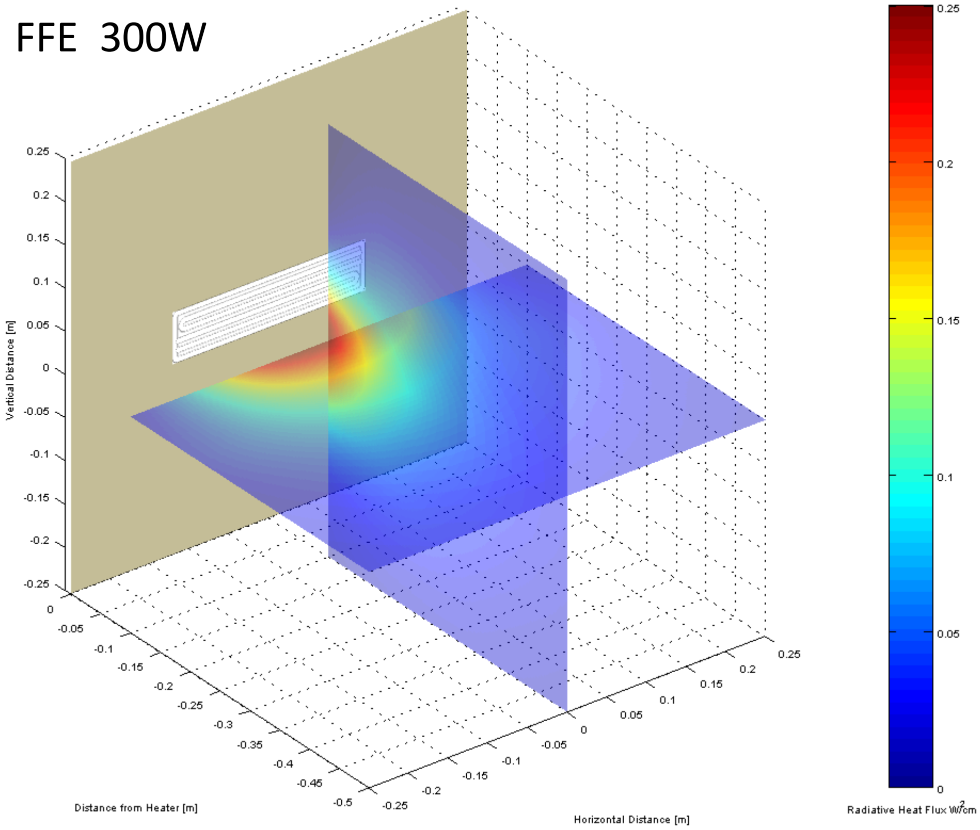

Figure 45: FFE 300W 3D heat flux profile, max heat flux @ 100mm ~0.25W/cm²

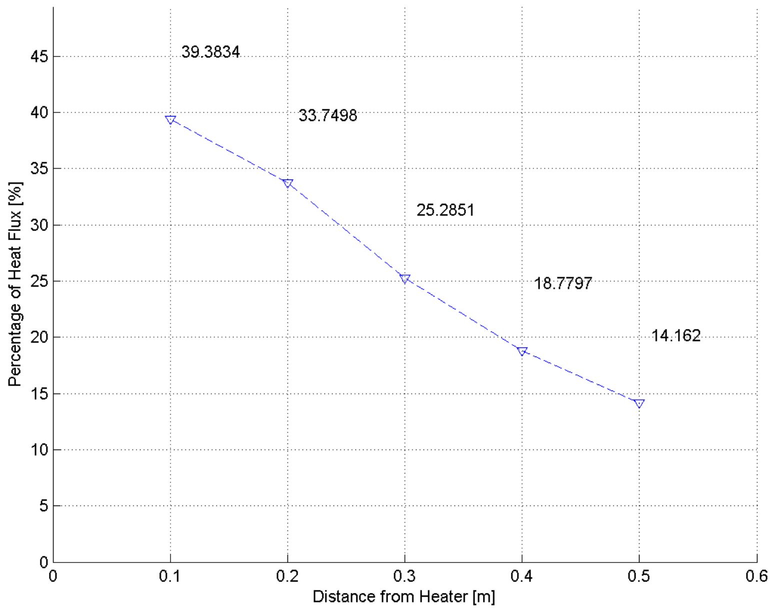

Figure 46: Percentage of input power measured at 500 x 500 mm grid, FFE 300W

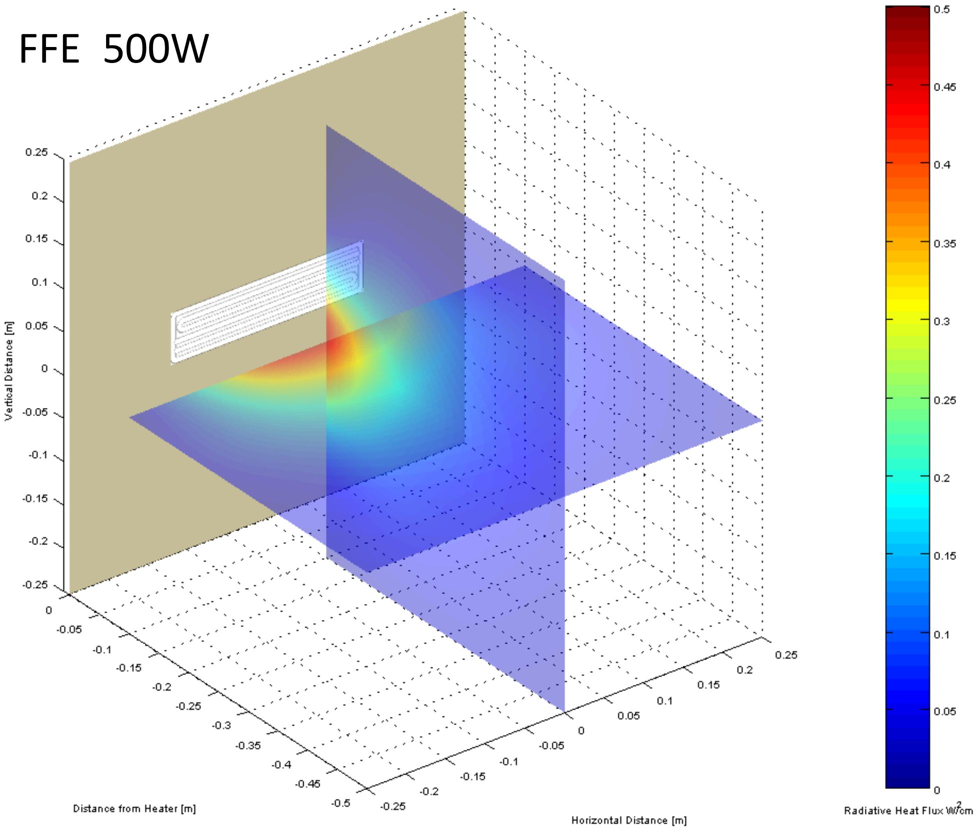

Figure 47: FFE 500W 3D heat flux profile, max heat flux @ 100mm ~0.47W/cm²

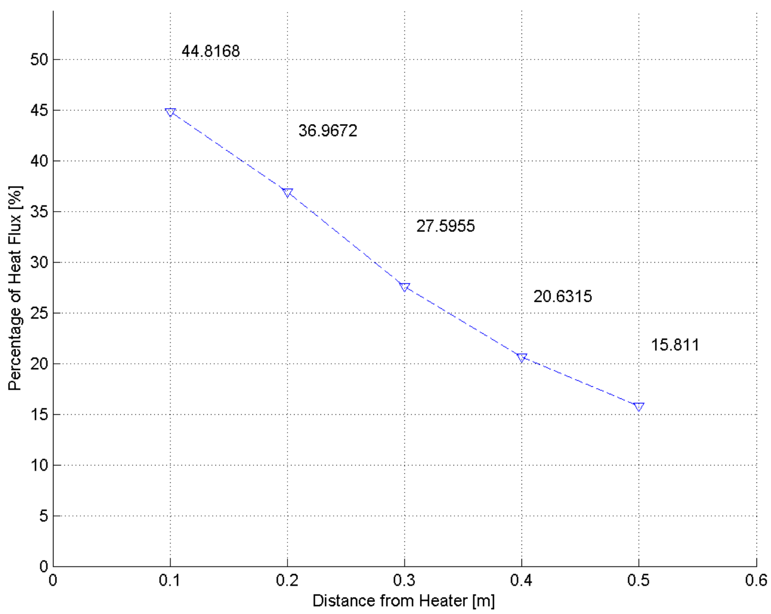

Figure 48: Percentage of input power measured at 500 x 500 mm grid, FFE 500W

FQE

Table 7: FQE Family, maximum heat flux measured (W/cm² at 100mm)

FQE	150W	500W	650W	1000W
	0.12	0.62	0.82	1.36

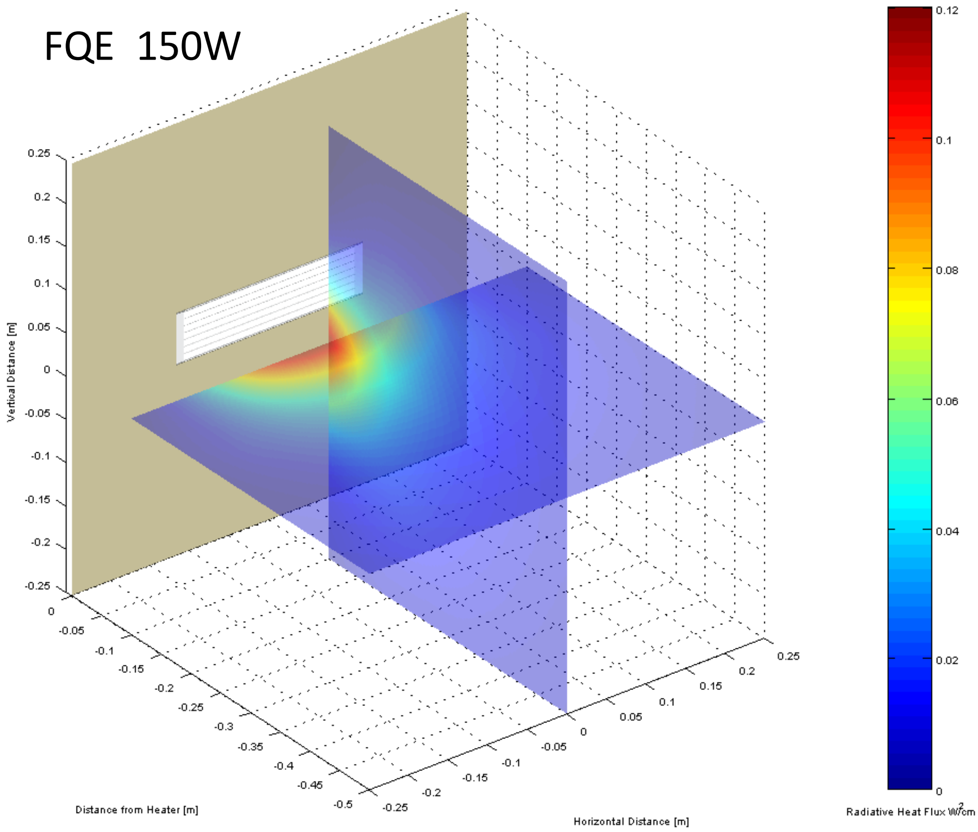

Figure 49: FQE 150W 3D heat flux profile, max heat flux @ 100mm ~0.12W/cm²

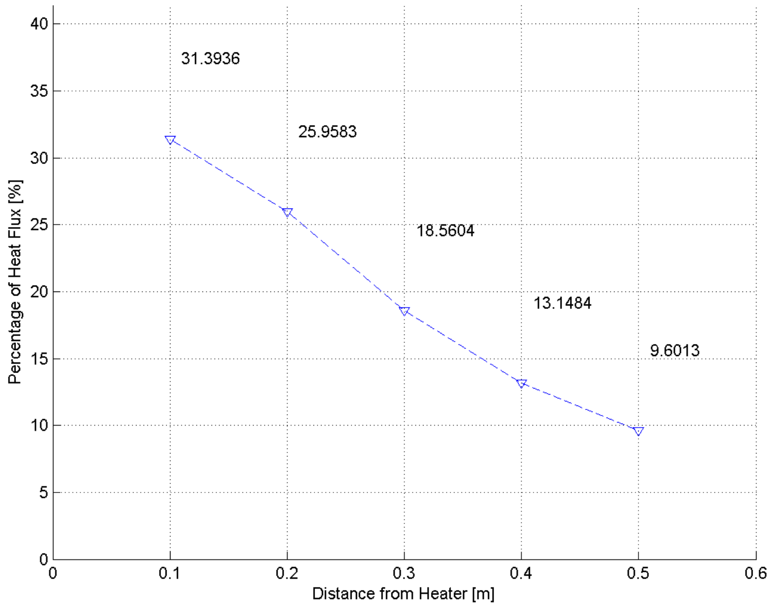

Figure 50: Percentage of input power measured at 500 x 500 mm grid, FQE 150W

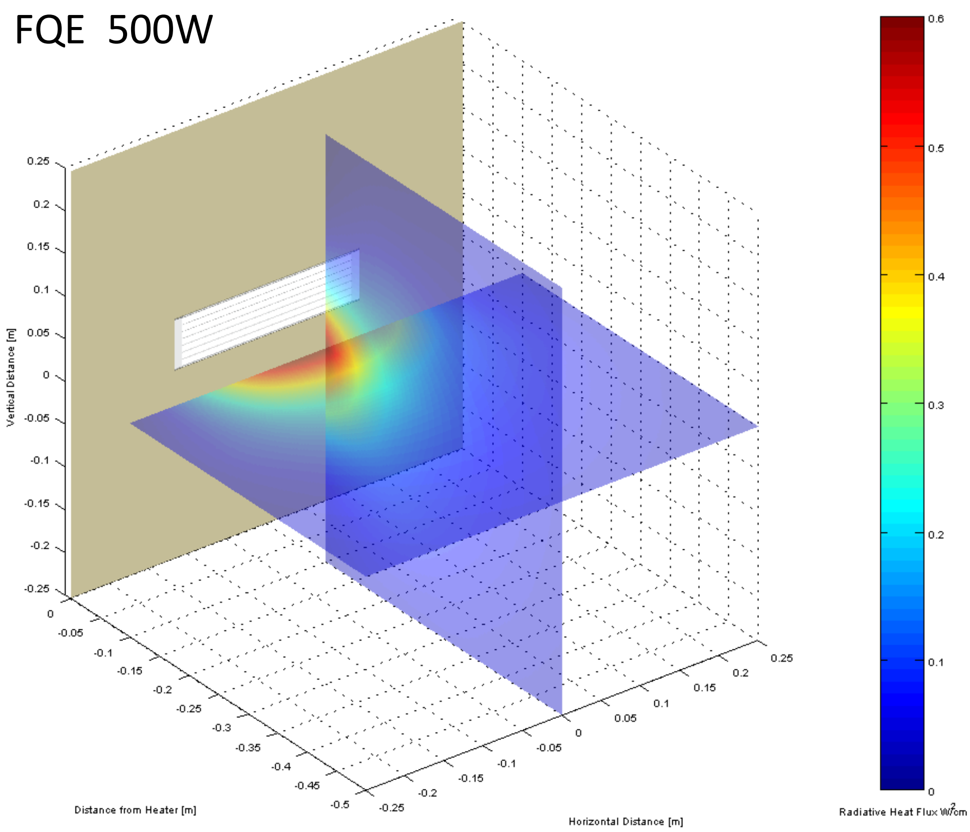

Figure 51: FQE 500W 3D heat flux profile, max heat flux @ 100mm ~0.62W/cm²

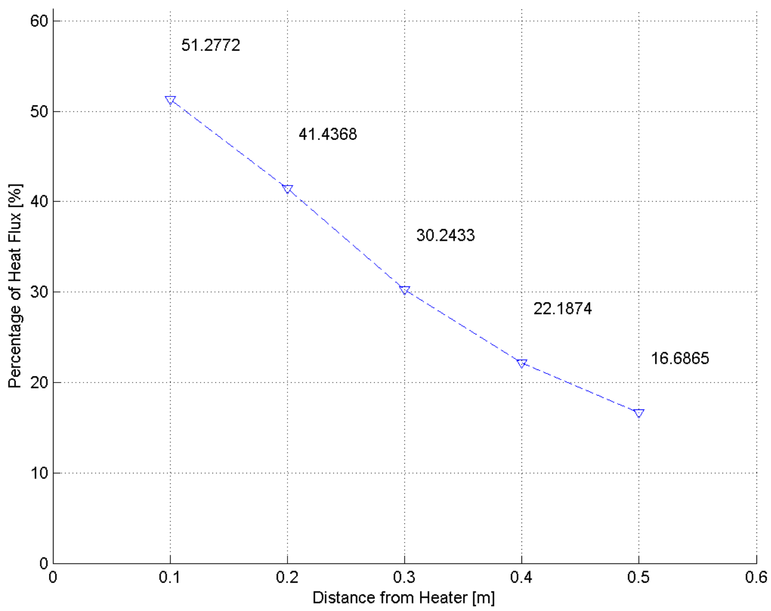

Figure 52: Percentage of input power measured at 500 x 500 mm grid, FQE 500W

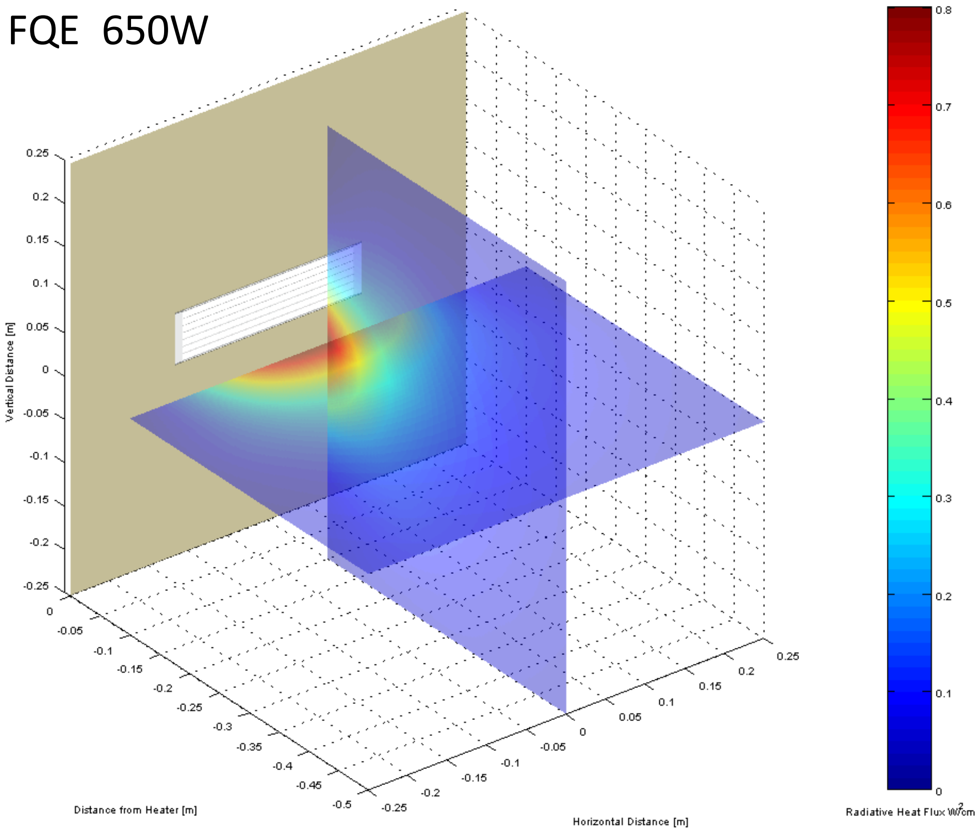

Figure 53: FQE 650W 3D heat flux profile, max heat flux @ 100mm ~0.82W/cm²

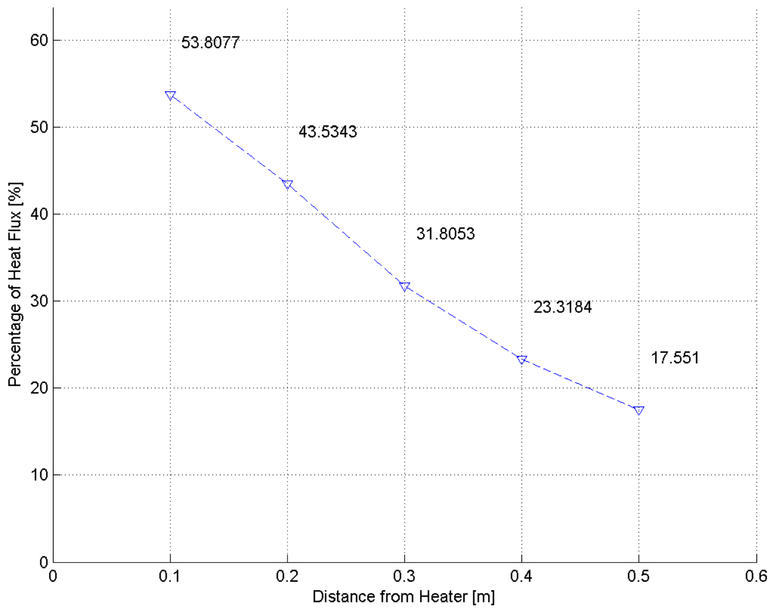

Figure 54: Percentage of input power measured at 500 x 500 mm grid, FQE 650W

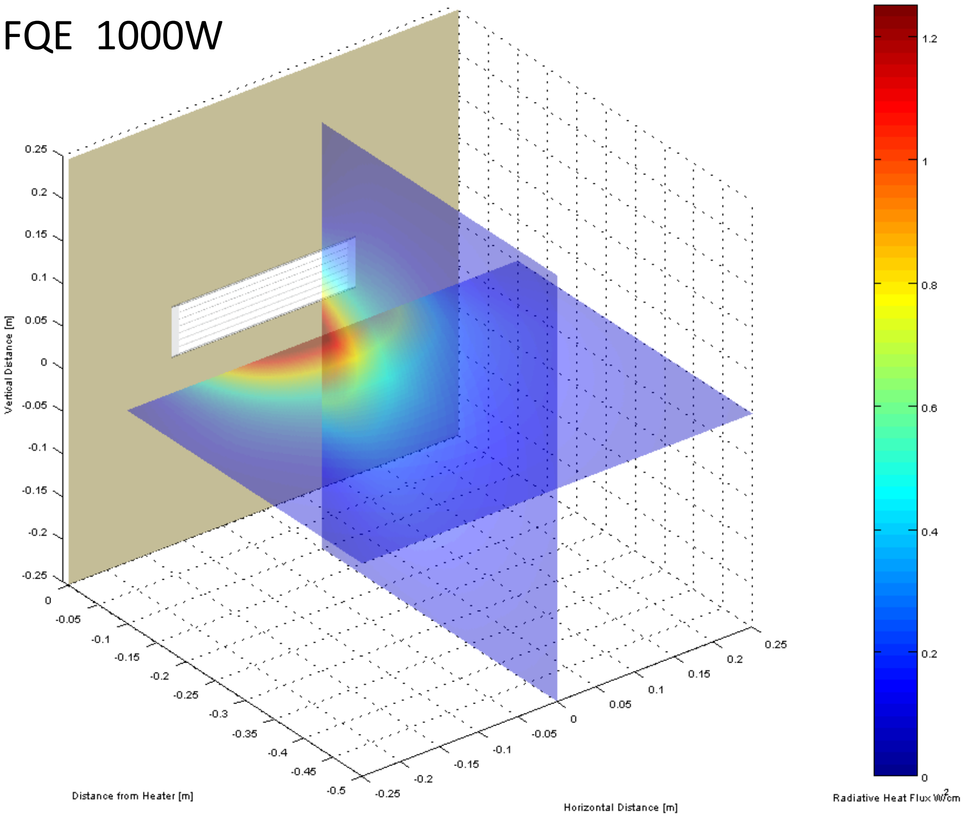

Figure 55: FQE 1000W 3D heat flux profile, max heat flux @ 100mm ~1.36W/cm²

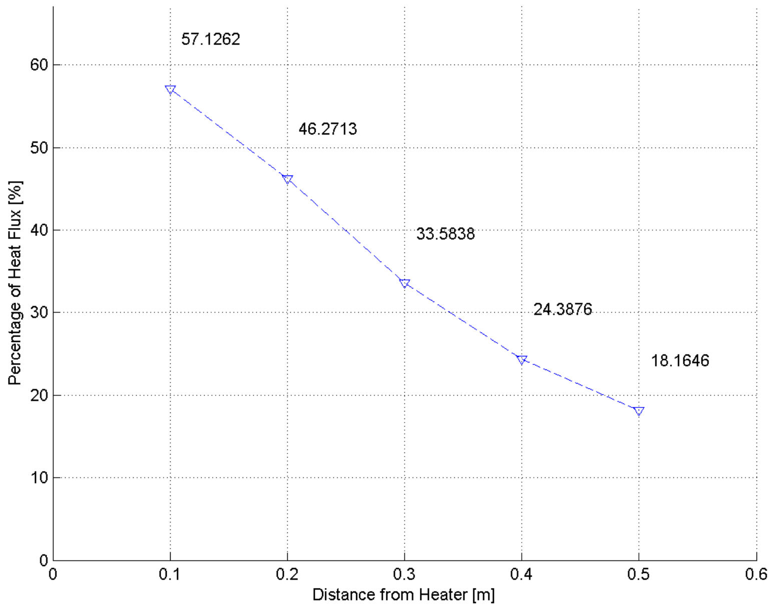

Figure 56: Percentage of input power measured at 500 x 500 mm grid, FQE 1000W

HQE

Table 8: HQE Family, maximum heat flux measured (W/cm² at 100mm)

HQE	250W	325W	500W
	0.39	0.50	0.89

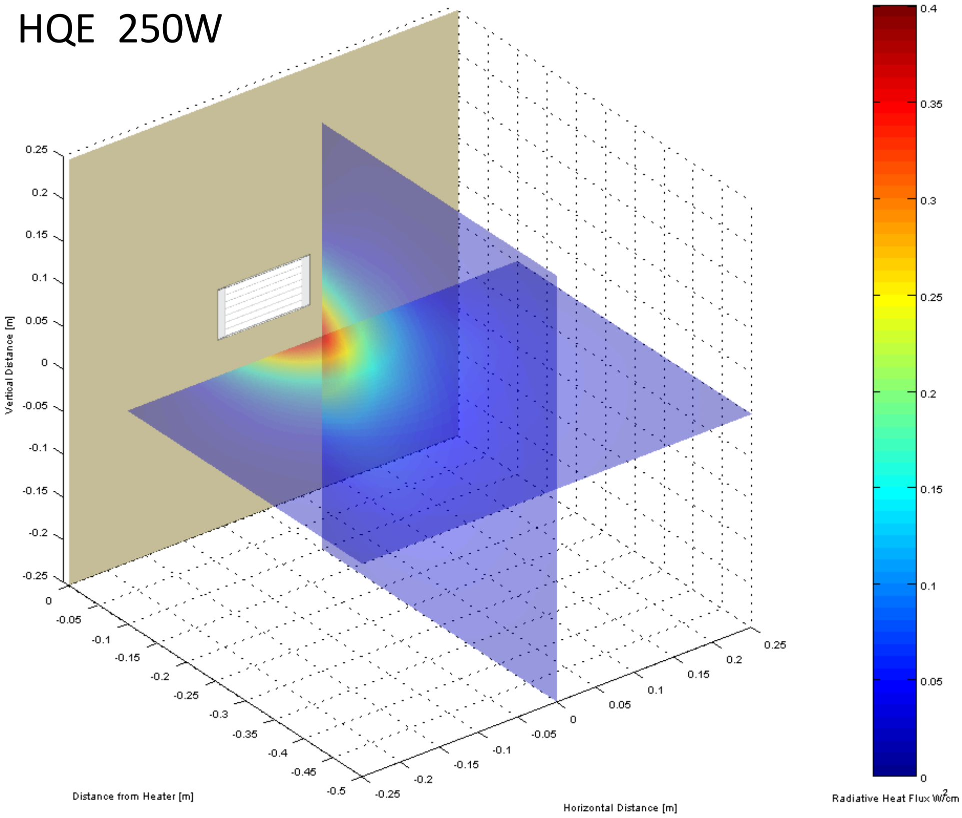

Figure 57: HQE 250W 3D heat flux profile, max heat flux @ 100mm ~0.39W/cm²

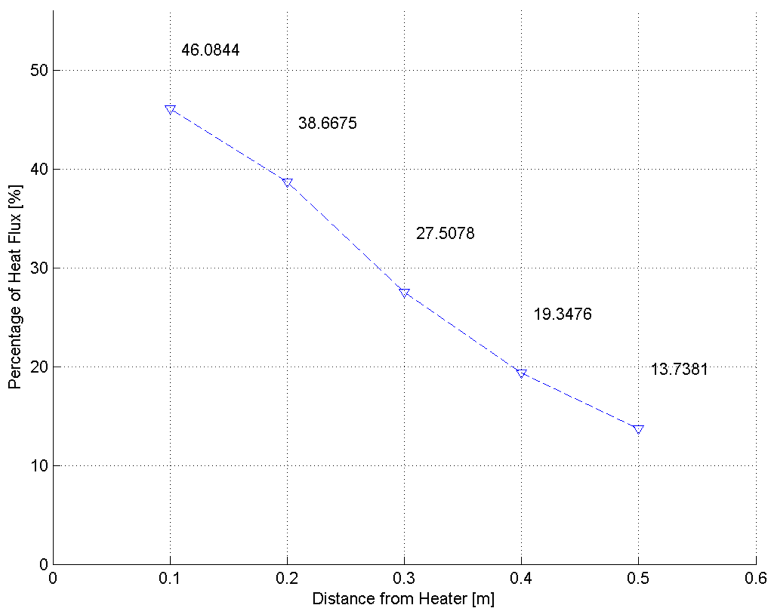

Figure 58: Percentage of input power measured at 500 x 500 mm grid, HQE 250W

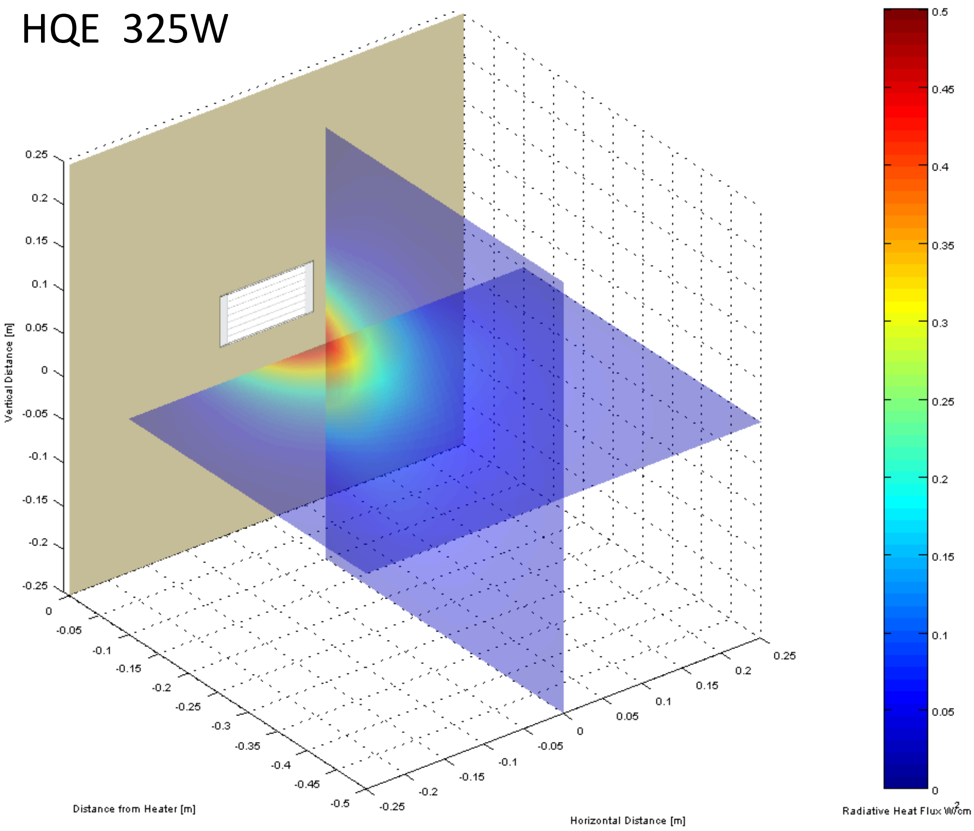

Figure 59: HQE 325W 3D heat flux profile, max heat flux @ 100mm ~0.50W/cm²

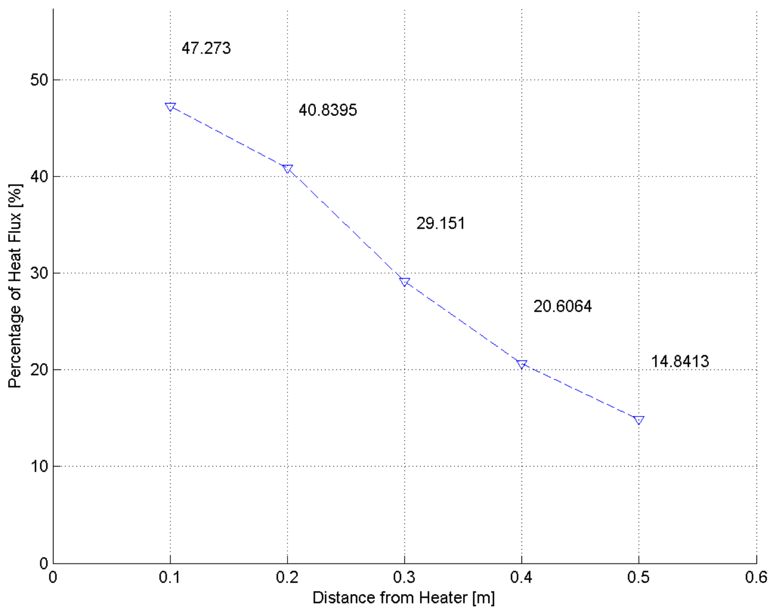

Figure 60: Percentage of input power measured at 500 x 500 mm grid, HQE 325W

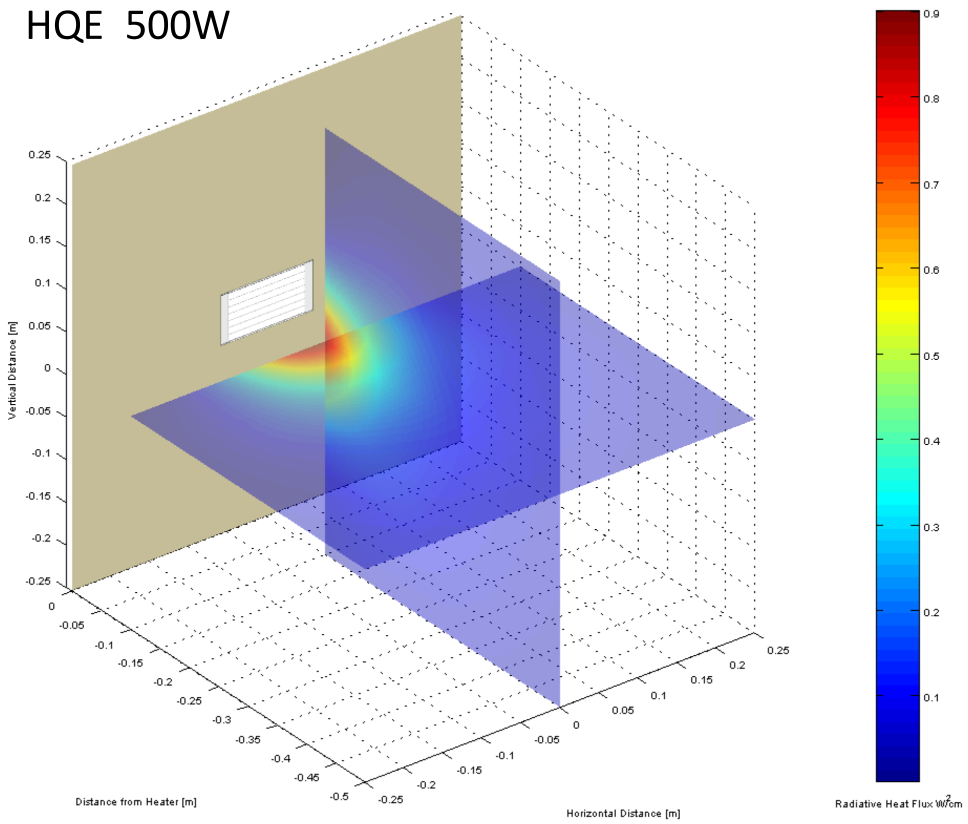

Figure 61: HQE 500W 3D heat flux profile, max heat flux @ 100mm ~0.89W/cm²

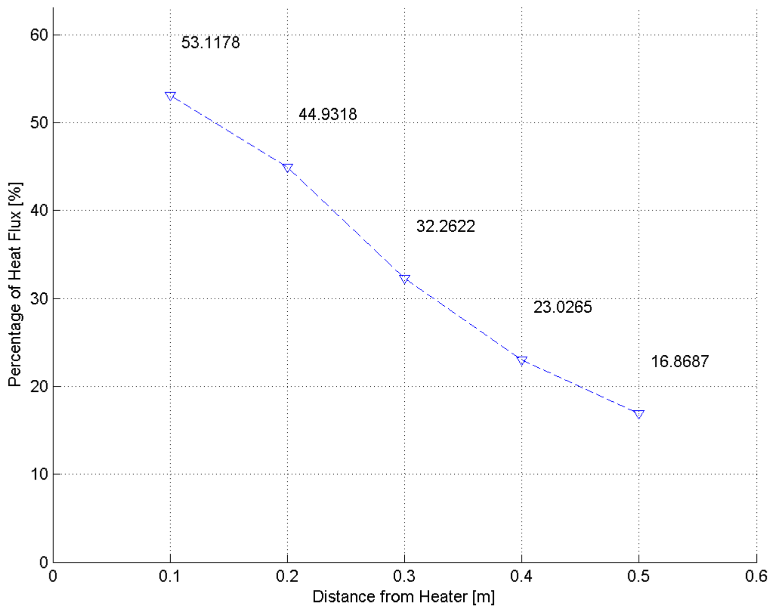

Figure 62: Percentage of input power measured at 500 x 500 mm grid, HQE 500W

SFSE

Table 9: SFSE Family, maximum heat flux measured (W/cm² at 100mm)

SFSE	250W	400W	650W	750W
	0.23	0.39	0.71	0.81

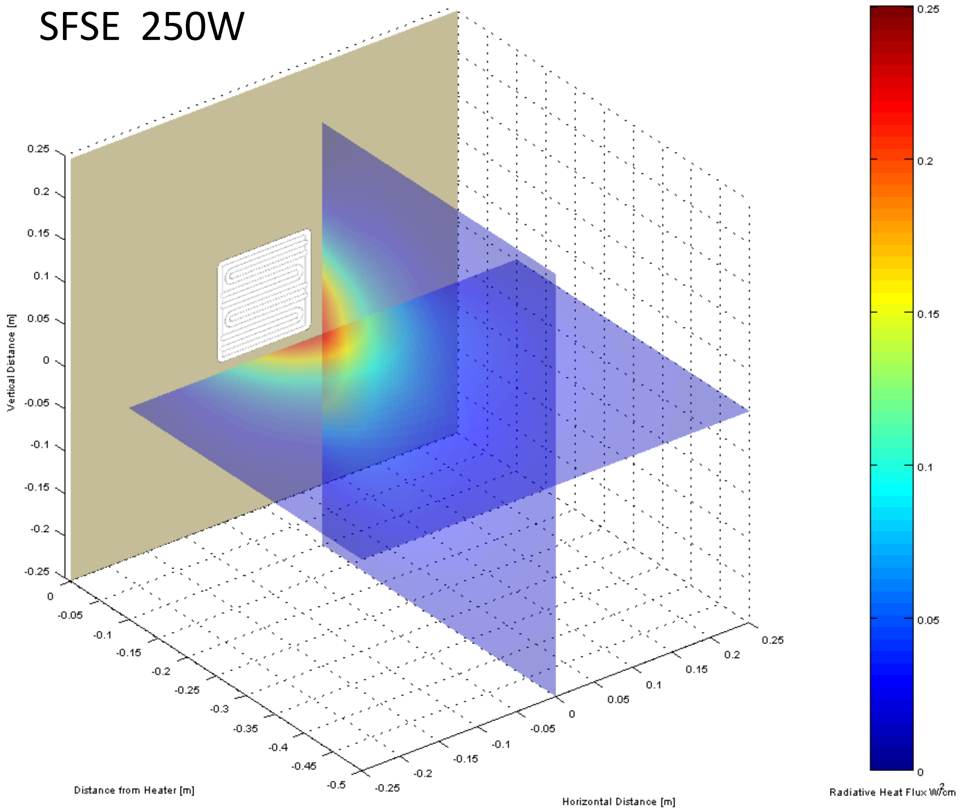

Figure 63: SFSE 250W 3D heat flux profile, max heat flux @ 100mm ~0.23W/cm²

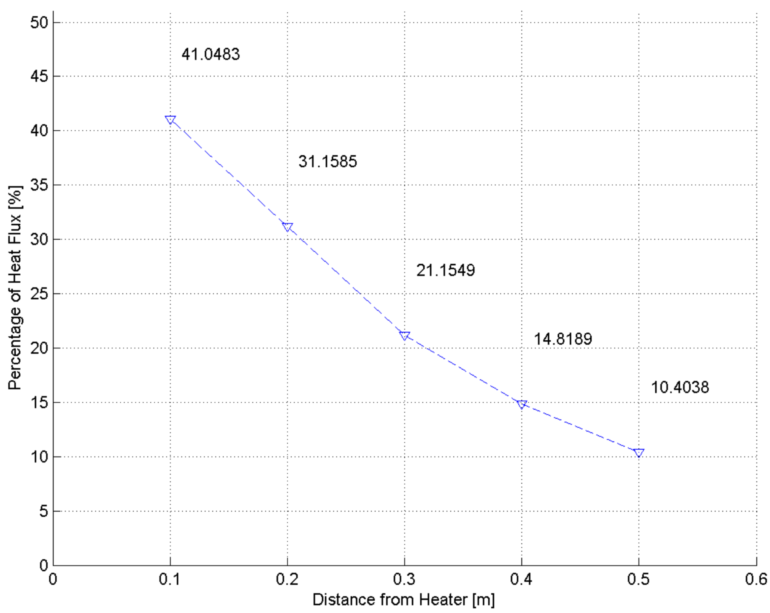

Figure 64: Percentage of input power measured at 500 x 500 mm grid, SFSE 250W

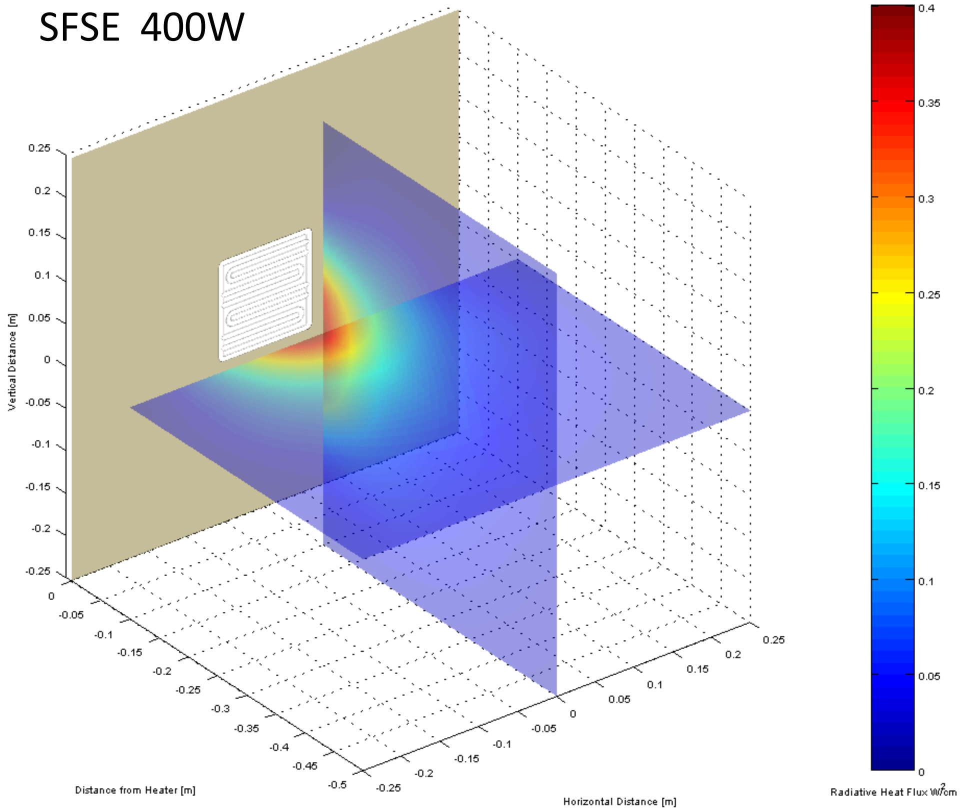

Figure 65: SFSE 400W 3D heat flux profile, max heat flux @ 100mm ~0.39W/cm²

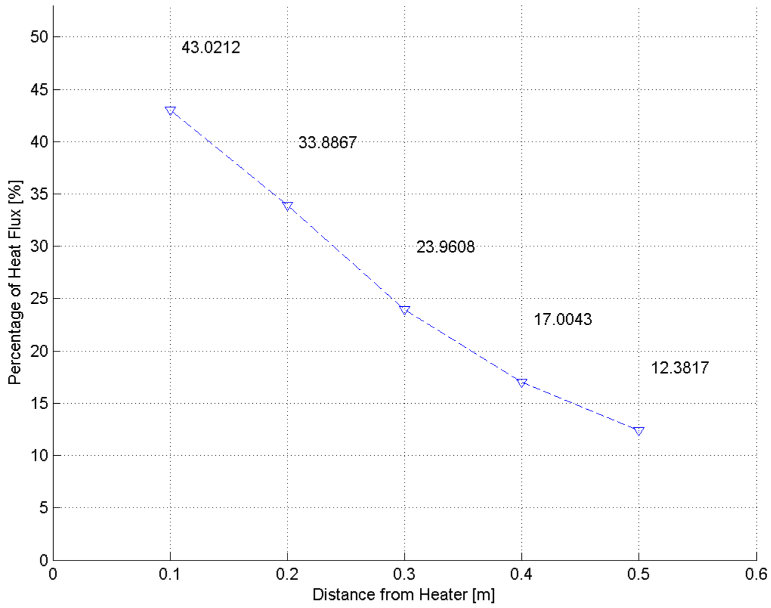

Figure 66: Percentage of input power measured at 500 x 500 mm grid, SFSE 400W

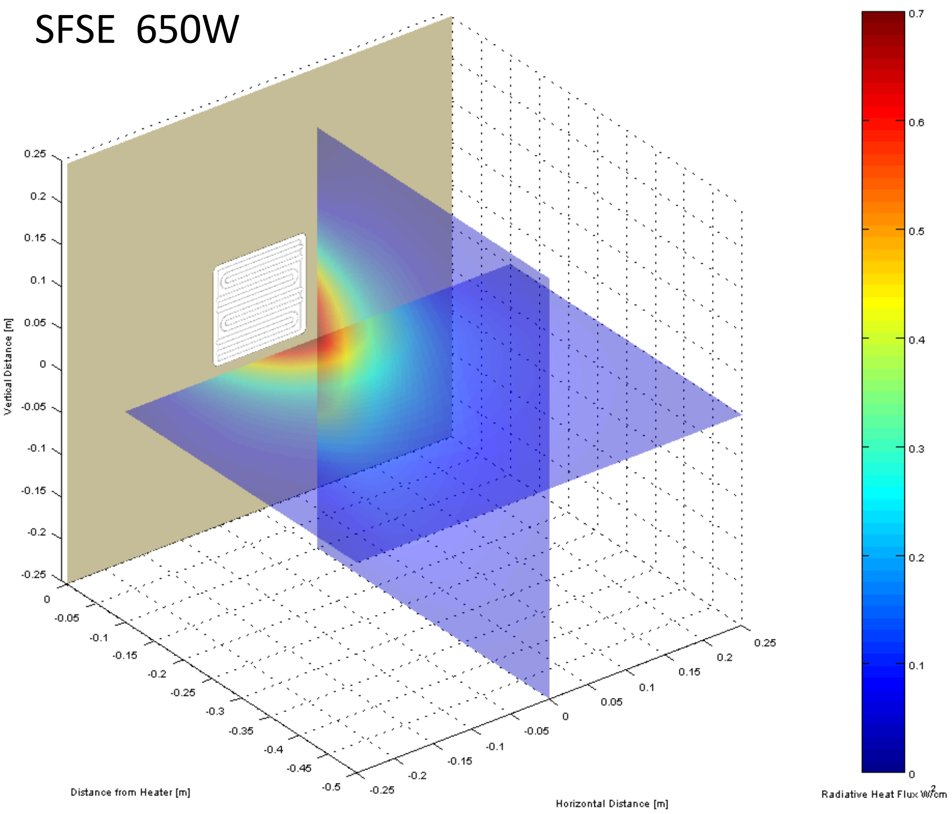

Figure 67: SFSE 650W 3D heat flux profile, max heat flux @ 100mm ~0.71W/cm²

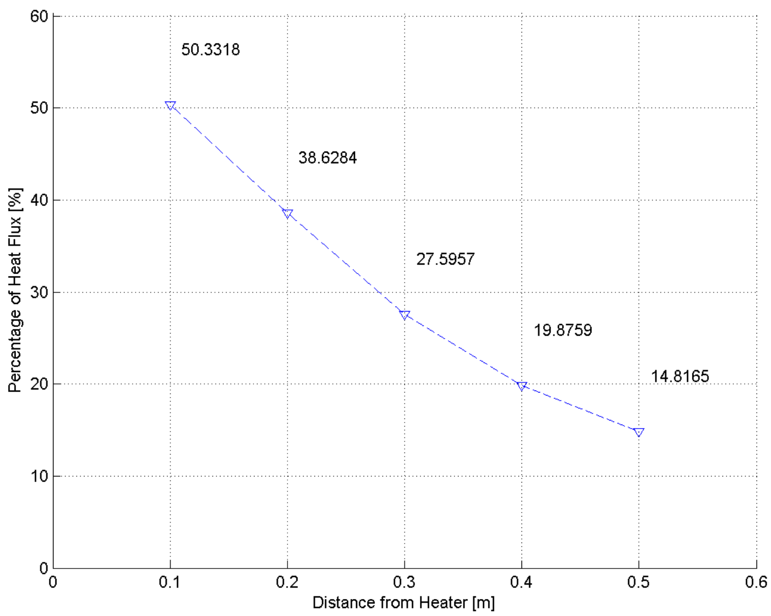

Figure 68: Percentage of input power measured at 500 x 500 mm grid, SFSE 650W

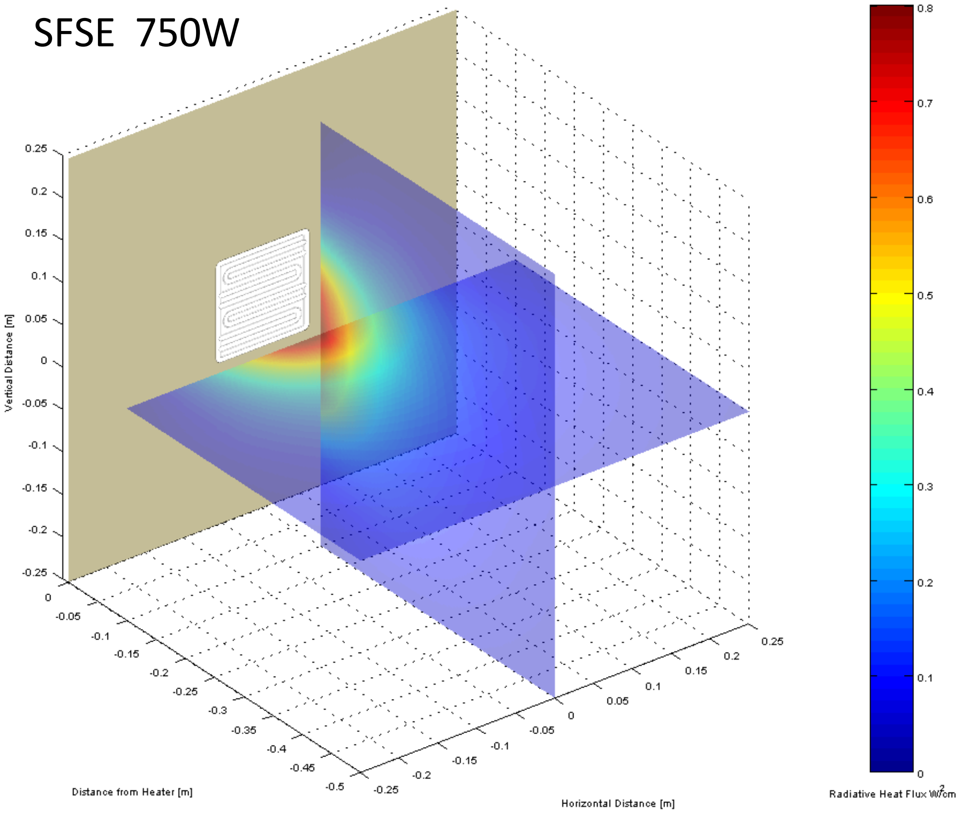

Figure 69: SFSE 750W 3D heat flux profile, max heat flux @ 100mm ~0.81W/cm²

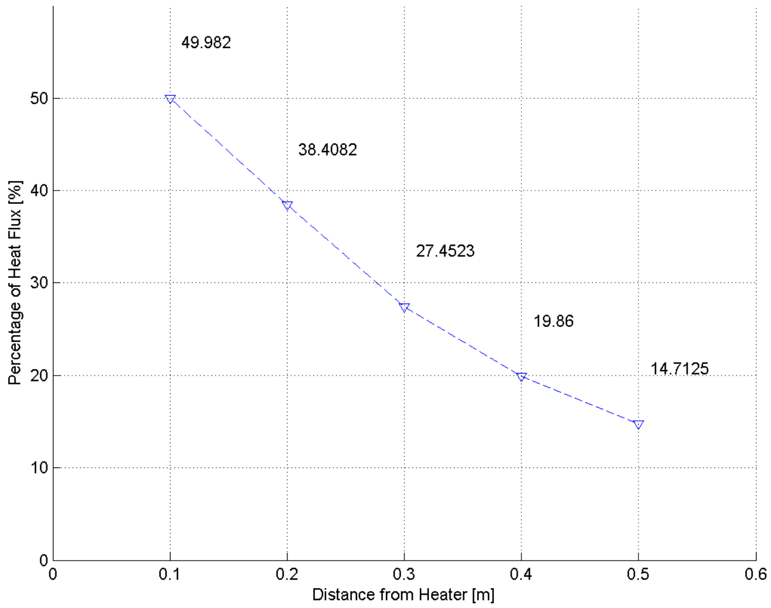

Figure 70: Percentage of input power measured at 500 x 500 mm grid, SFSE 750W

SFEH

Table 10: SFEH Family, maximum heat flux measured (W/cm² at 100mm)

SFEH	250W	400W	600W	800W
	0.28	0.51	0.81	1.18

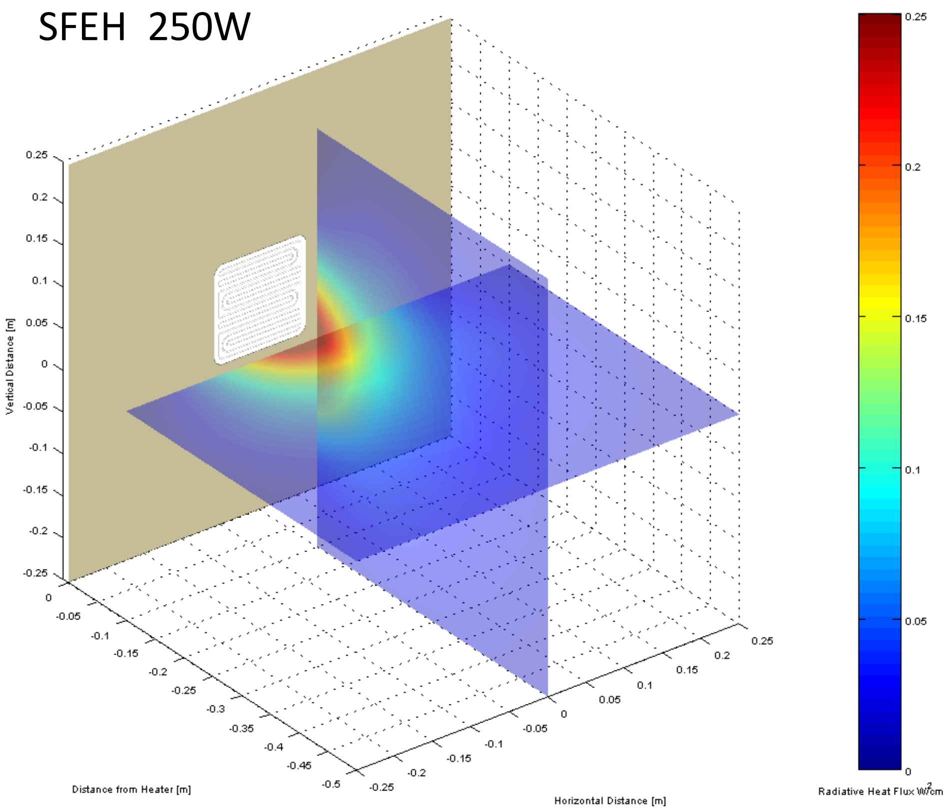

Figure 71: SFEH 250W 3D heat flux profile, max heat flux @ 100mm ~0.28W/cm²

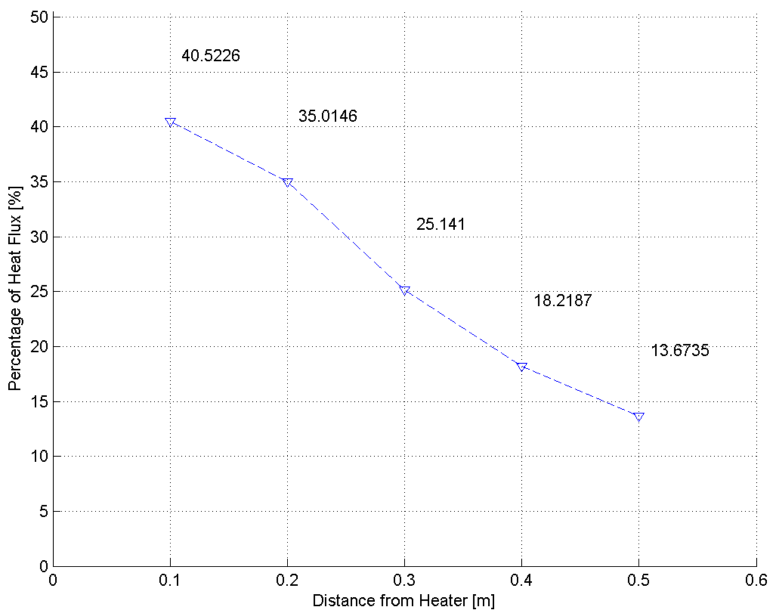

Figure 72: Percentage of input power measured at 500 x 500 mm grid, SFEH 250W

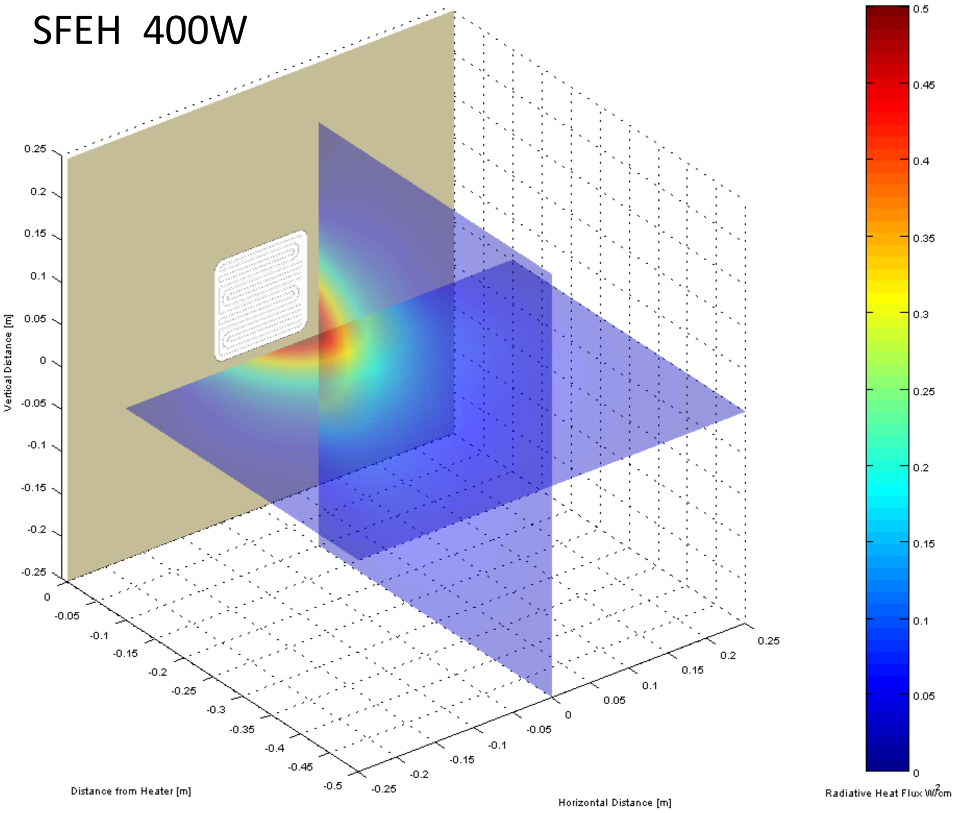

Figure 73: SFEH 400W 3D heat flux profile, max heat flux @ 100mm ~0.51W/cm²

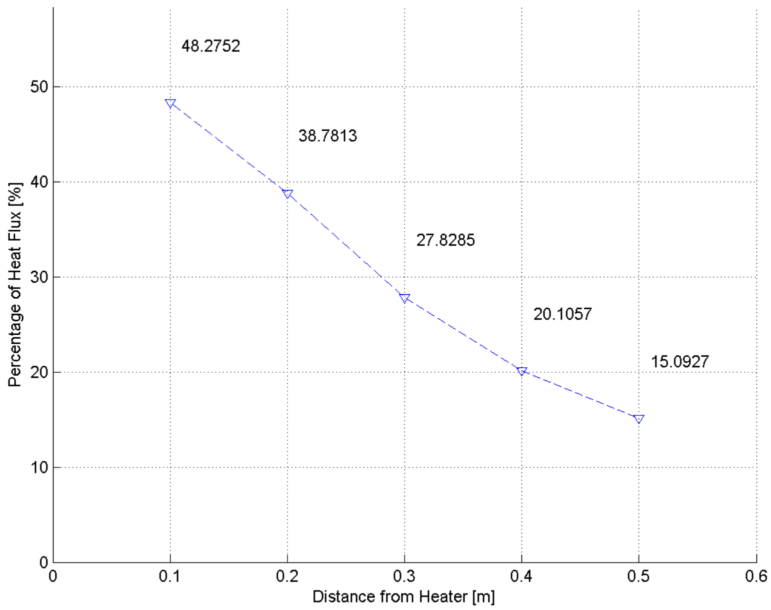

Figure 74: Percentage of input power measured at 500 x 500 mm grid, SFEH 400W

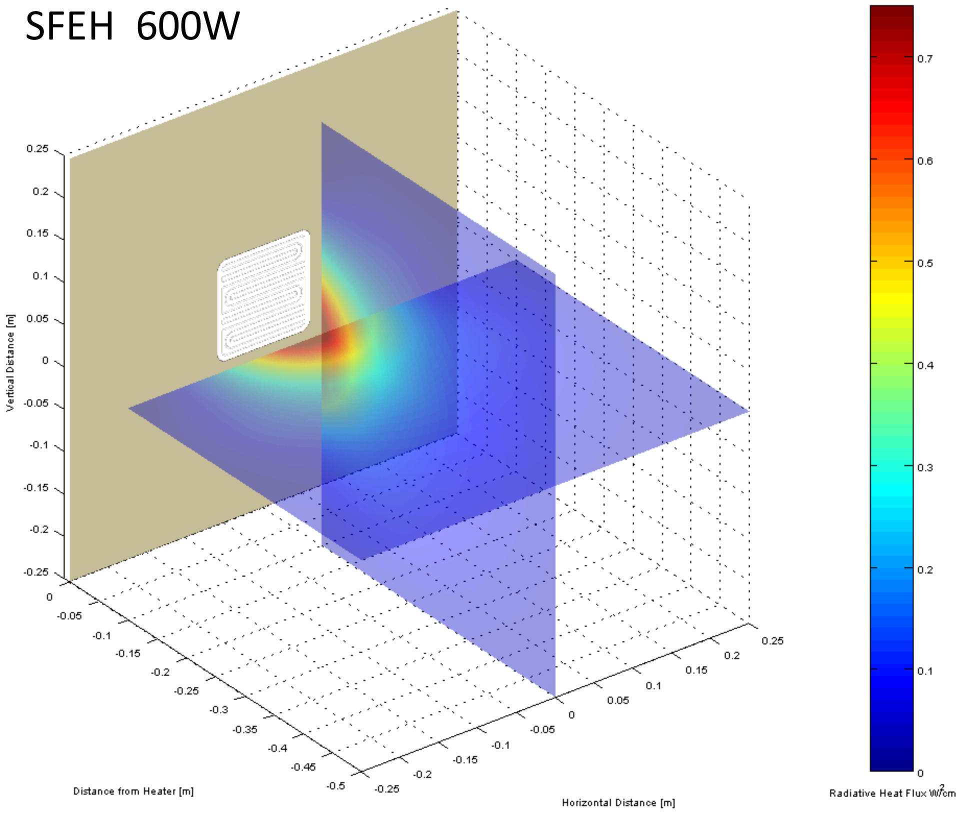

Figure 75: SFEH 600W 3D heat flux profile, max heat flux @ 100mm ~0.81W/cm²

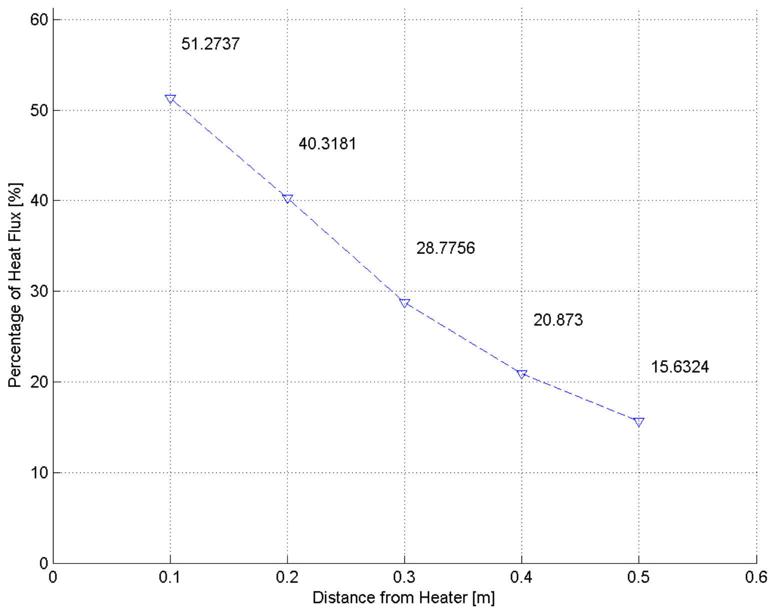

Figure 76; Percentage of input power measured at 500 x 500 mm grid, SFEH 600W

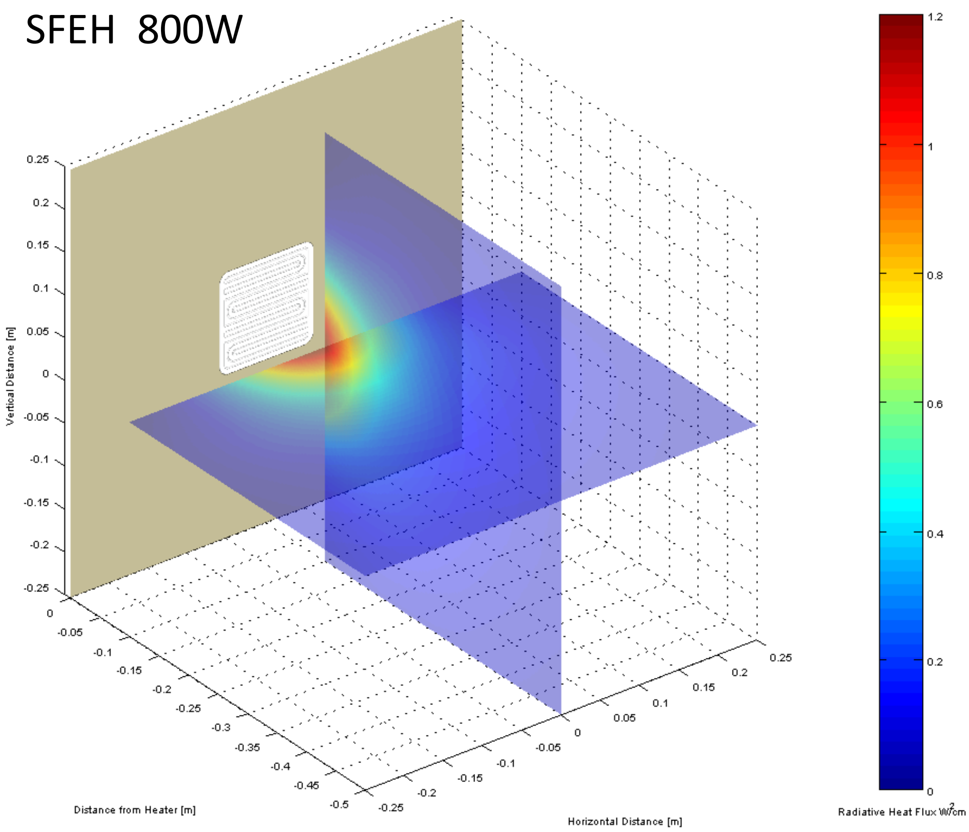

Figure 77: SFEH 800W 3D heat flux profile, max heat flux @ 100mm ~1.18W/cm²

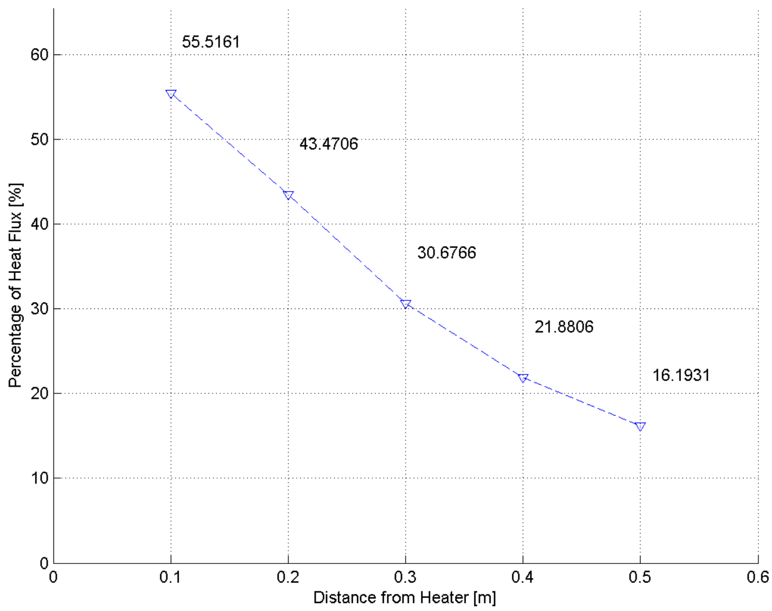

Figure 78: Percentage of input power measured at 500 x 500 mm grid, SFEH 800W

Note.

All data presented in this report is given with the good intention of assisting the customer in their heat work design process. When interpreting the data presented throughout this report, it is important to stress that field conditions may not necessarily match those in the laboratory setting. The actual material used and process conditions will strongly affect how infrared energy is absorbed, thus temperatures and heat flux values may differ from those quoted here. In addition, process environment factors (dust, chemicals, vibration) may also impinge on lifetimes and performance of elements. Therefore this information is to be used as a guide to end users in their process design and no guarantee of performance is implied.

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