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INTERIM REPORT

Final Lab Test Report Radiant Heating and Cooling Systems

April 2011

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Executive Summary

The objective of this project is to develop and demonstrate a residential radiant HVAC system with peak load shifting on the cooling system. The major components of the system include radiant panels, water chiller, water heater, pumps and controls, and the hydronic distribution system. This report covers the laboratory testing of the radiant panel prototypes to determine if the design would be adequate for the residential heating and cooling loads expected in the field for California hot/dry climates in the central valley and desert climate zones.

Two panel prototypes developed by the Western Cooling Efficiency Center were tested in a chamber built at the Gas Technology Institute for testing, the manifold panel and the tube panel. The manifold panel was designed with parallel tubes and headers sandwiched between a 5 mil aluminum facing and a fiberglass board. The tube panel design included a 32 mil aluminum sheet, a single tube in a serpentine shape, and a fiberglass board. The two panels were mounted on a ceiling and tested for heating and cooling performance.

A nominal 10 ft. by 10 ft. by 8 ft. room was built for testing purposes. The room was made from standard residential construction components. A mini-split heat pump was used to heat and cool the room to near the setpoint, and then a series of wound tubing on the floor of the room was used to introduce the radiant load on the panels. A laboratory-grade heating and cooling system was built to both introduce the load and supply the panels with heated and cooled water at controlled flow rates for the test.

For radiant performance testing, 32 tests were run in the laboratory – 11 for heating and 22 for cooling. An additional 27 tests were performed to assess the impact of a convective load for the heating season conditions and temperature stratification in the room. The results of the tests were that the panels provided a heat flux of 16 to 18 Btu/hr/ft^2 for the heating season and 10 to 12 Btu/hr/ft^2 for the cooling season (negative heat flux in this report). The impact of introducing a 100 cfm fan in the heating season was significant, increasing the heat flux by 50%. A similar result is expected for the cooling season.

The tests supported the performance of these designs as a good solution for radiant HVAC system panels in a residential environment. While the manifold design had better performance, the added complexity and risk of leaks in the large number of fittings favors the more simple tubular design.

Addition tests on convection in the cooling season, the impact of painting the surface on heat flux, and the use of an above-the ceiling web of tubes placed below the insulation were identified and may be conducted if resources are available.

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Lab Test Apparatus

A new lab test apparatus was built for testing the radiant panels in this project. The apparatus consists of the following major components:

The chamber – a nominal 10 ft. by 10 ft. by 8 ft. tall room build from lumber, insulation, and drywall. A 1 ton Sanyo mini-split heat pump was used for heating and cooling the space to precondition the room, and a series of tubes was placed on the floor and wall to provide the load for testing.

The HVAC system – this system was designed to both provide the load for testing and provide a controlled volume of heated and cooled water to the panels. Sub-components include the water chiller, water heater, pumps and controls, hydronic distribution system, chiller heat exchanger and 300 gallon chilled water storage tank.

Instrumentation – A Labview Fieldpoint data acquisition system was used. One set of modules were designed to operate pumps and the chiller in response from the computer-based data acquisition system, and another set was used for collecting data on temperatures, flow volumes, and relative humidity in the chamber.

Several figures follow showing system components.

Figure 1 Test Chamber

Figure 2 Chilled Water Storage Tank (Background): Plumbing System and Chilled Water Heat Exchanger (Foreground)

Figure 3 Mini-split Heat Pump (Foreground); Mini-Split Chiller for Chilled Water Production (Background)

Figure 4 High Efficiency Water Heater with Side-Mounted Heat Exchanger for Panel Hot Water Supply

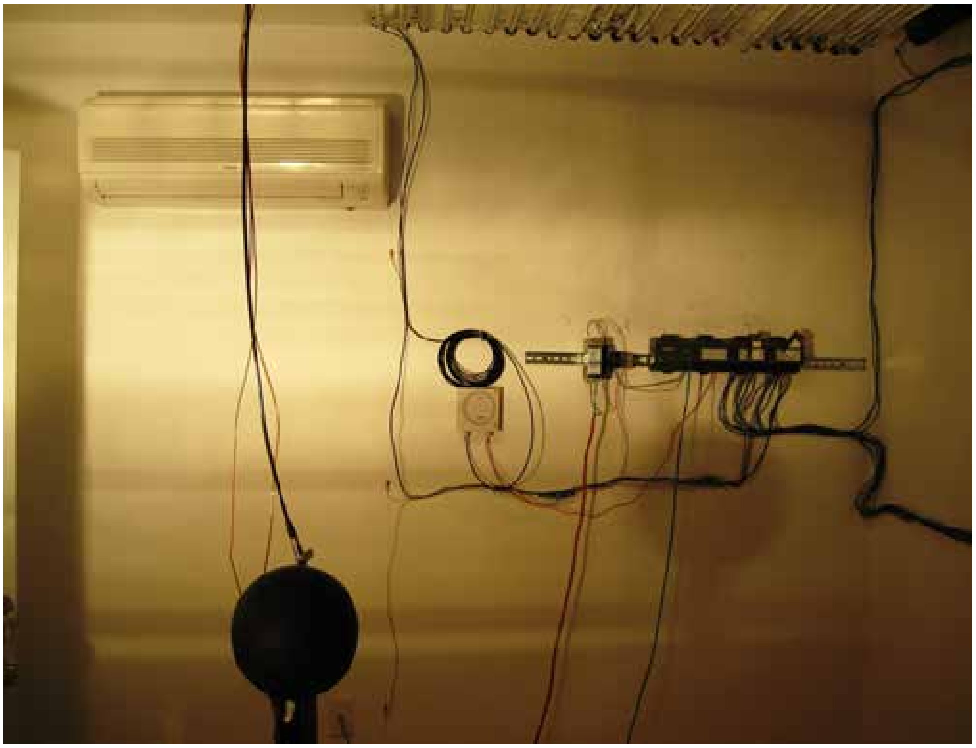

Figure 5 MRT Globe, RH Sensor, Wall-Mounted Thermocouples, and Labview Fieldpoint Modules

Figure 6 300 Pulses per Gallon Water Meter

Radiant Panel Design Details

Two radiant panel prototypes were designed for testing. The manifold panel uses a parallel tubing arrangement leading to headers on opposite sides. The tubing is sandwiched between a 5 mil aluminum sheet and a high density fiberglass board. The tubing panel uses a single tube in a serpentine shape sandwiched between a 32 mil aluminum sheet and high density fiberglass board. Details of the two panel designs are as follows:

Manifold Panel (also see Figure 7 Manifold Panel):

- Size – nominal 4 ft. x 8 ft. (actual 48.75 inches by 97.125 inches)
- Aluminum thickness – 5 mil (.005 inches)
- Fiberglass board thickness and density – 1 inch, 7 lb. per cubic ft density
- Tubing material, size, layout – HDPE, manifold layout with tubes 2 inches apart
- Mounting method – screw into ceiling joists with large washers or screw into ceiling joists through manifold end framing
- Design issues – approximately 100 tube connections can leak

Figure 7 Manifold Panel

Tube Panel (also see Figure 8 Tube Panel):

- Size – nominal 4 ft. x 8 ft. (actual 48.25 inches by 104.00 inches)
- Aluminum thickness – 32 mil (.032 inches)
- Fiberglass board thickness and density – 1 inch, 7 lb. per cubic ft density
- Tubing material, size, layout – HDPE, serpentine layout with tubes 6 inches apart
- Mounting method – screw into ceiling joists; small washers may be needed
- Design issues – more robust design

Figure 8 Tube Panel

Test Plan

The following summary includes several changes that were made after the system shakedown was concluded. (The test plan was provided in detail in the *Radiant HVAC Test Plan* report.)

Radiant Heating Tests

The nominal operating conditions for the radiant heating system were 120 OF delivered water temperature, 0.3 gpm, and a chamber (room) temperature of 68 OF. That condition was expected to produce a heat flux in the range of 15 to 20 Btu/hr/ft2. Each of the main conditions was varied to determine the impact of a normal range of variation on the performance of the panel. The room temperature was varied from 60 OF to 74 OF in five increments. The supply water temperature was varied from 80 OF to 140 OF in five increments. The water flow rate was varied from 0.1 gpm to 0.5 gpm in five increments. These 15 tests, summarized below in Figure 9, were the basis for the radiant heating performance testing.

Test Number	Water Inlet Temp. (^oF)	Water Flow Rate (gpm)	Chamber Temp (^oF)
1h	120	0.3	60
2h	120	0.3	64
3h	120	0.3	68
4h	120	0.3	70
5h	120	0.3	74
6h	80	0.3	68
7h	100	0.3	68
3h	120	0.3	68
8h	130	0.3	68
9h	140	0.3	68
10h	120	0.1	68
11h	120	0.2	68
12h	120	0.3	68
13h	120	0.4	68
14h	120	0.5	68

Figure 9 Heating Test Conditions

Radiant Cooling Tests

The nominal operating conditions for the radiant cooling system were 58 ^OF delivered water temperature, 0.5 gpm, and a chamber (room) temperature of 78 ^OF. That condition was expected to produce a heat absorption (negative flux) in the range of 10 to 12 Btu/hr/ft^2. Each of the main conditions was varied to determine the impact of a normal range of variation on the performance of the panel. The room temperature was varied from 70 ^OF to 85 ^OF in four increments. The supply water temperature was varied from 50 ^OF to 68 ^OF in three increments. The water flow rate was varied from 0.1 gpm to 0.5 gpm in five increments. These 12 tests, summarized below in Figure 10, were the basis for the radiant heating performance testing.

Test Number	Water Inlet Temp. (ºF)	Water Flow Rate (gpm)	Chamber Temp (ºF)
1	58	0.5	70
2	58	0.5	75
3	58	0.5	80
4	58	0.5	85
5	50	0.5	78
6	58	0.5	78
7	68	0.5	78
8	58	0.1	78
9	58	0.2	78
10	58	0.3	78
11	58	0.4	78
12	58	0.5	78

Figure 10 Cooling Test Conditions

Convective Heating Tests

Convective heating test were performed to determine if the radiant performance of the heating system could be improved by the addition of a fan in the conditioned space (such as a ceiling fan). For the tube panel, all 15 tests were re-run and for the manifold panel tests 1, 3, 5, 6, 9, 10, 12, and 14 were run with a 100 cfm blower operating in the room (mini-split indoor section shown in Figure 5). Cooling tests were not run for the convective condition.

Stratification Tests

Four tests were run to measure the stratification of air temperatures from floor to ceiling as a way of assessing the comfort of the occupants. Test 6 in the cooling table was run for both panels, and test 3h in the heating table was run for both panels. RTDs were mounted in a vertical line in the center of the room (not immediately below either panel) at 1 ft. increments beginning at the floor and stopping at 8 ft.

Raw Data Collected

Data was collected every 5 seconds for the tests identified and logged into the GTI network. The following data was collected for each test:

1. Time
2. Elapsed Time
3. Relative Humidity
4. Water Storage Chilled Water HX Inlet Temperature
5. Water Storage Chilled Water HX Outlet Temperature
6. Manifold Panel Surface Temp - South
7. Manifold Panel Surface Temp - Center
8. Manifold Panel Surface Temp - North
9. Tube Panel Surface Temp - South
10. Tube Panel Surface Temp - Center
11. Tube Panel Surface Temp - North
12. South Wall - 25"
13. South Wall - 49.75"
14. South Wall - 74.875"
15. West Wall - 25"
16. West Wall - 49.75"
17. West Wall - 74.875"
18. North Wall - 25"
19. North Wall - 49.75"
20. North Wall - 74.875'
21. East Wall - 25"
22. East Wall - 49.75"
23. East Wall - 74.875"
24. Ambient Room Temperature
25. MRT Globe Temperature
26. Manifold Panel Water Temperature Inlet

27. Manifold Panel Water Temperature Outlet
28. Tube Panel Water Temperature Inlet
29. Tube Panel Water Temperature Outlet
30. Water Heater HX Inlet
31. Water Heater HX Outlet
32. Water Heater Inlet
33. Water Heater Outlet
34. Chilled Water Storage Supply
35. Chilled Water Storage Return
36. Panel Return Water Flow Rate
37. Water Storage Supply Water Flow Rate
38. Panel Supply Water Flow Rate
39. Gas Meter (gas cubic ft)
40. Panel Water Flow Rate (meter in chamber)

From these values, the following were calculated for each test:

1. Average Water Inlet Temp
2. Average Water Outlet Temp
3. Average Water Flow Rate
4. Center of Panel Surface Temp
5. Average Chamber Temp
6. Average Room RH
7. Panel Heat Flux

An example of the raw data file is provided below in Figure 11. A full set of raw data files is available from GTI.

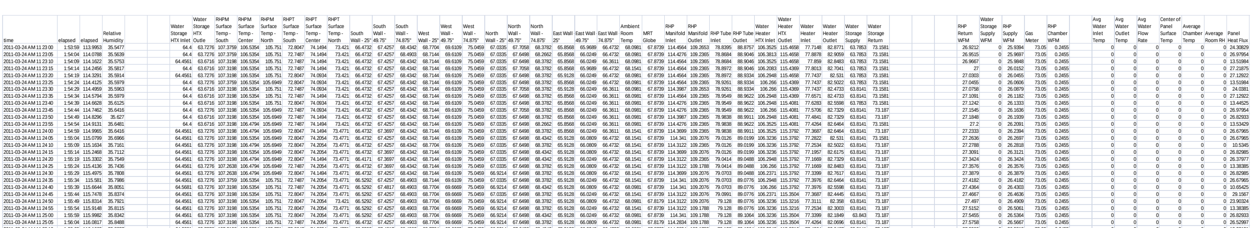

Figure 11 Raw Data File (example not readable)

Data Analysis

Raw data was analyzed to identify the performance of the panels with the operating conditions identified. The results of each test are provided in the tables below.

Test Number	Water Inlet Temp. (°F)	Water Flow Rate (gpm)	Chamber Temp (°F)	Avg Water Inlet Temp (°F)	Avg Water Outlet Temp (°F)	Avg Water Flow Rate (gpm)	Center of Panel Surface Temp (°F)	Average Chamber Temp (°F)	Average Room RH (%RH)	Heat Flux (Btu/hr/ft²)
1h	120	0.3	60	116.73	112.15	0.304	103.47	60.66	58.63	19.79
2h	120	0.3	64							
3h	120	0.3	68	116.39	112.35	0.303	104.60	65.99	47.51	17.56
4h	120	0.3	70							
5h	120	0.3	74	116.83	113.31	0.301	106.44	72.41	46.06	15.04
6h	80	0.3	68	74.41	74.12	0.335	73.69	66.75	42.75	1.41
7h	100	0.3	68							
3h	120	0.3	68	116.30	112.43	0.310	104.47	67.32	37.94	17.16
8h	130	0.3	68							
9h	140	0.3	68	133.83	128.62	0.302	118.42	68.53	49.57	22.47
10h	120	0.1	68	115.53	107.25	0.099	102.10	67.82	42.59	11.62
11h	120	0.2	68							
12h	120	0.3	68	116.30	112.43	0.310	104.47	67.32	37.94	17.16
13h	120	0.4	68							
14h	120	0.5	68	116.67	114.27	0.495	105.57	67.84	39.70	17.02

Figure 12 Radiant Heating Tube Panel

Test Number	Water Inlet Temp. (°F)	Water Flow Rate (gpm)	Chamber Temp (°F)	Avg Water Inlet Temp (°F)	Avg Water Outlet Temp (°F)	Avg Water Flow Rate (gpm)	Center of Panel Surface Temp (°F)	Average Chamber Temp (°F)	Average Room RH (%RH)	Heat Flux (Btu/hr/ft²)
1h	120	0.3	60	115.32	109.67	0.315	106.41	60.21	67.13	25.33
2h	120	0.3	64							
3h	120	0.3	68	115.47	109.77	0.305	106.78	68.17	33.28	24.76
4h	120	0.3	70							
5h	120	0.3	74							
6h	80	0.3	68							
7h	100	0.3	68							
3h	120	0.3	68							
8h	130	0.3	68							
9h	140	0.3	68							
10h	120	0.1	68							
11h	120	0.2	68							
12h	120	0.3	68							
13h	120	0.4	68							
14h	120	0.5	68							

Figure 13 Radiant Heating Manifold Panel (test stopped due to leaking panel)

Test Number	Water Inlet Temp. (^oF)	Water Flow Rate (gpm)	Chamber Temp (^oF)	Avg Water Inlet Temp (^oF)	Avg Water Outlet Temp (^oF)	Avg Water Flow Rate (gpm)	Center of Panel Surface Temp (^oF)	Average Chamber Temp (^oF)	Average Room RH (%RH)	Heat Flux (Btu/hr/ft²)
1	58	0.5	70	58.09	58.97	0.513	63.38	70.03	38.02	-6.40
2	58	0.5	75	57.57	58.89	0.511	65.07	74.36	33.95	-9.62
3	58	0.5	80	57.43	59.50	0.498	68.18	80.27	32.24	-14.74
4	58	0.5	85	57.95	60.25	0.498	70.37	84.39	28.79	-16.43
5	50	0.5	78	50.13	52.81	0.495	63.61	77.51	27.74	-18.93
6	58	0.5	78	58.17	59.76	0.502	67.13	78.46	31.47	-11.40
7	68	0.5	78	68.00	68.72	0.497	72.47	78.17	33.89	-5.15
8	58	0.1	78	57.88	62.48	0.150	68.00	77.08	31.93	-9.79
9	58	0.2	78	58.32	61.38	0.205	67.74	77.46	37.56	-8.95
10	58	0.3	78	57.97	60.34	0.318	67.20	77.35	36.49	-10.76
11	58	0.4	78	58.24	60.16	0.406	66.93	77.37	35.98	-11.11
12	58	0.5	78	57.87	59.56	0.498	66.87	77.83	34.16	-12.01

Figure 14 Radiant Cooling Tube Panel

Test Number	Water Inlet Temp. (^oF)	Water Flow Rate (gpm)	Chamber Temp (^oF)	Avg Water Inlet Temp (^oF)	Avg Water Outlet Temp (^oF)	Avg Water Flow Rate (gpm)	Center of Panel Surface Temp (^oF)	Average Chamber Temp (^oF)	Average Room RH (%RH)	Heat Flux (Btu/hr/ft²)
1	58	0.5	70	57.71	58.18	0.492	71.84	71.27	33.83	-3.34
2	58	0.5	75							
3	58	0.5	80	58.74	59.62	0.504	80.13	79.65	31.74	-6.30
4	58	0.5	85	57.80	58.81	0.493	85.49	83.23	26.40	-7.14
5	50	0.5	78	49.96	52.39	0.518	62.26	77.42	26.65	-17.96
6	58	0.5	78	58.26	59.00	0.512	78.41	77.91	33.19	-5.42
7	68	0.5	78	68.35	68.74	0.505	77.65	77.08	29.16	-2.81
8	58	0.1	78	58.48	60.11	0.126	77.93	77.74	30.44	-2.93
9	58	0.2	78							
10	58	0.3	78	58.39	59.37	0.312	77.69	77.71	33.18	-4.34
11	58	0.4	78							
12	58	0.5	78	58.50	59.29	0.489	78.21	77.49	30.17	-5.53

Figure 15 Radiant Cooling Manifold Panel

Test Number	Water Inlet Temp. (°F)	Water Flow Rate (gpm)	Chamber Temp (°F)	Avg Water Inlet Temp (°F)	Avg Water Outlet Temp (°F)	Avg Water Flow Rate (gpm)	Center of Panel Surface Temp (°F)	Average Chamber Temp (°F)	Average Room RH (%RH)	Heat Flux (Btu/hr/ft²)
1h	120	0.3	60	115.87	107.97	0.277	96.49	60.88	30.51	28.21
2h	120	0.3	64	116.45	110.49	0.299	100.09	63.49	28.97	24.49
3h	120	0.3	68	117.01	111.45	0.314	101.40	65.98	28.09	24.91
4h	120	0.3	70	116.54	111.32	0.321	101.73	67.64	27.82	23.95
5h	120	0.3	74	116.41	111.27	0.296	102.95	73.44	41.90	21.59
6h	80	0.3	68	73.42	72.71	0.295	71.67	67.13	29.66	2.98
7h	100	0.3	68	107.03	101.90	0.295	93.06	66.56	27.82	21.65
3h	120	0.3	68	117.01	111.45	0.314	101.40	65.98	28.09	24.91
8h	130	0.3	68	125.05	117.85	0.293	106.74	66.33	27.46	30.16
9h	140	0.3	68	134.11	125.94	0.293	113.70	65.96	28.12	34.17
10h	120	0.1	68	114.60	102.81	0.111	95.87	66.24	37.52	18.83
11h	120	0.2	68	115.88	108.08	0.206	99.21	67.10	30.99	22.97
12h	120	0.3	68	116.11	110.84	0.300	101.00	66.95	38.83	22.77
13h	120	0.4	68	116.98	112.55	0.393	101.76	67.02	31.44	24.82
14h	120	0.5	68	115.42	112.13	0.508	101.14	67.43	41.87	23.82

Figure 16 Convective Heating Tube Panel

Test Number	Water Inlet Temp. (°F)	Water Flow Rate (gpm)	Chamber Temp (°F)	Avg Water Inlet Temp (°F)	Avg Water Outlet Temp (°F)	Avg Water Flow Rate (gpm)	Center of Panel Surface Temp (°F)	Average Chamber Temp (°F)	Average Room RH (%RH)	Heat Flux (Btu/hr/ft²)
1h	120	0.3	60	114.55	107.06	0.307	103.91	62.36	60.44	32.73
2h	120	0.3	64							
3h	120	0.3	68	115.93	109.53	0.301	106.59	67.57	47.38	27.50
4h	120	0.3	70							
5h	120	0.3	74	116.15	110.38	0.303	107.90	73.04	39.89	24.90
6h	80	0.3	68	73.97	73.13	0.304	72.13	66.26	57.68	3.67
7h	100	0.3	68							
3h	120	0.3	68	115.93	109.53	0.301	106.59	67.57	47.38	27.50
8h	130	0.3	68							
9h	140	0.3	68	132.01	123.18	0.298	120.02	67.65	59.47	37.55
10h	120	0.1	68	114.82	100.83	0.099	100.99	67.33	46.19	19.85
11h	120	0.2	68							
12h	120	0.3	68	115.93	109.53	0.301	106.59	67.57	47.38	27.50
13h	120	0.4	68							
14h	120	0.5	68	116.61	112.31	0.511	107.68	67.77	35.81	31.34

Figure 17 Convective Heating Manifold Panel

								Vertical Location, ft								
Test Number	Avg Water Inlet Temp (°F)	Avg Water Outlet Temp (°F)	Avg Water Flow Rate (gpm)	Center of Panel Surface Temp (°F)	Average Chamber Temp (°F)	Average Room RH (%RH)	Heat Flux (Btu/hr/ft²)	0	1	2	3	4	5	6	7	8
6 Manifold Cooling	58.38	59.78	0.500	70.66	77.29	31.55	-9.93	76.80	77.52	77.56	77.40	77.48	77.56	77.48	77.49	77.19
6 Tube Cooling	58.16	59.78	0.506	67.05	77.25	31.35	-11.69	76.85	77.54	77.66	77.55	77.58	77.64	77.55	77.64	76.17
3h Tube Heating	115.72	112.21	0.323	104.36	68.81	36.75	16.20	68.23	67.54	67.74	67.83	68.11	68.49	68.76	69.30	74.32
3h Manifold Heating	115.47	109.77	0.305	106.78	68.17	33.28	24.76	66.02	66.33	66.73	67.26	67.82	68.42	68.71	69.52	74.69

Figure 18 Temperature Stratification Testing

The following notes apply to raw data collection and data analysis:

1. Where case 3h is shown in the water inlet temperature test group, it was repeated for some of the tests to measure variance and not repeated for others. There was no significant difference in the result
2. The setpoints for each test were the nominal condition desired for each test, in some cases the actual room temperature, supply water temperature, or flow rates varied.
3. The average room temperature reported included all the wall and ambient air temperatures measured to better characterize the radiant environment.
4. MRT temperatures were collected. There was no significant difference between the MRT temperature and the bare RTD temperature near the MRT globe.
5. Tests were not randomized – they were performed in the order shown.

Discussion

For the radiant heating tests, the performance of the panel was most strongly dependant on the delivered water temperature, then the chamber temperature, then the flow rate. The flow rate is significant up to 0.3 gpm and then levels off. At 0.3 gpm and 120 F delivered water temperature, expect 15 – 17 Btu/hr/ft^2 heat flux or 510 to 600 Btu/hr for a 34 sq ft panel.

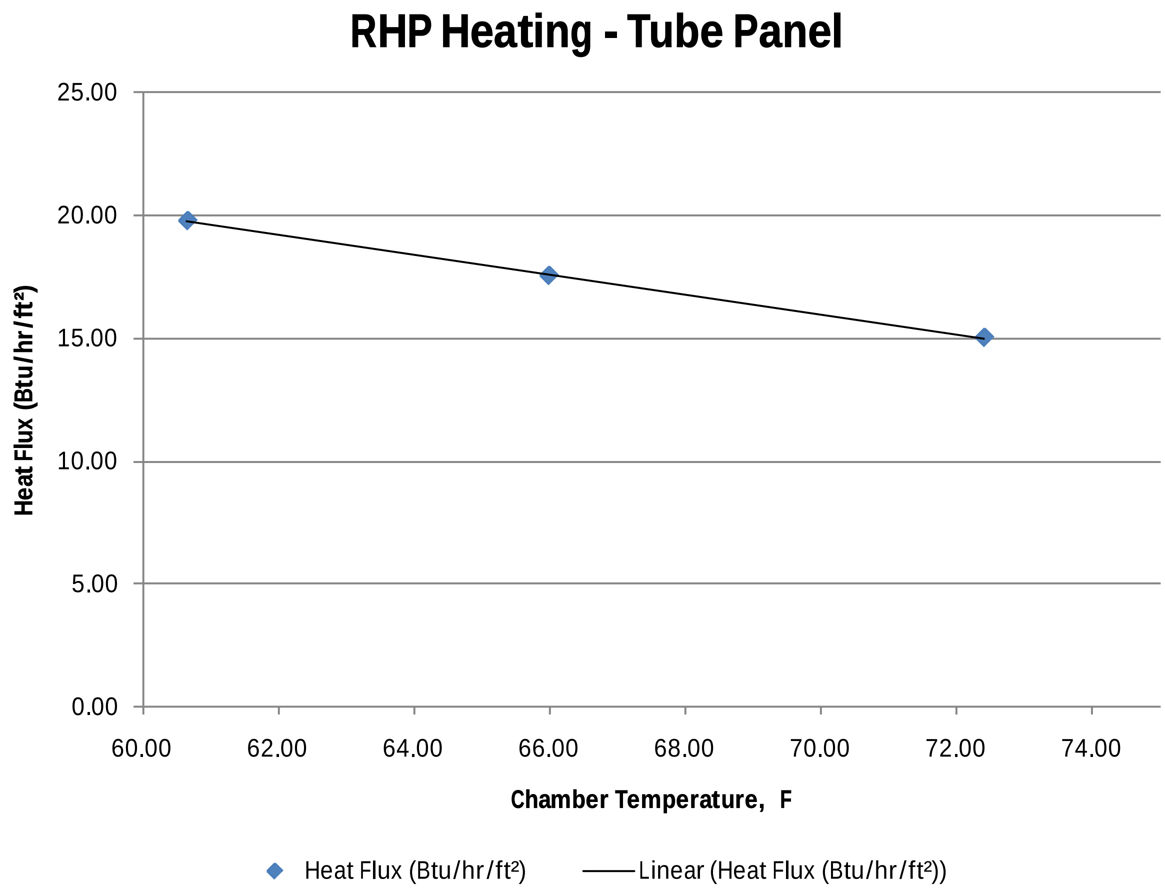

Figure 19 Effect of Chamber Temperature on Heat Flux for Tube Panel in Radiant Heating Mode

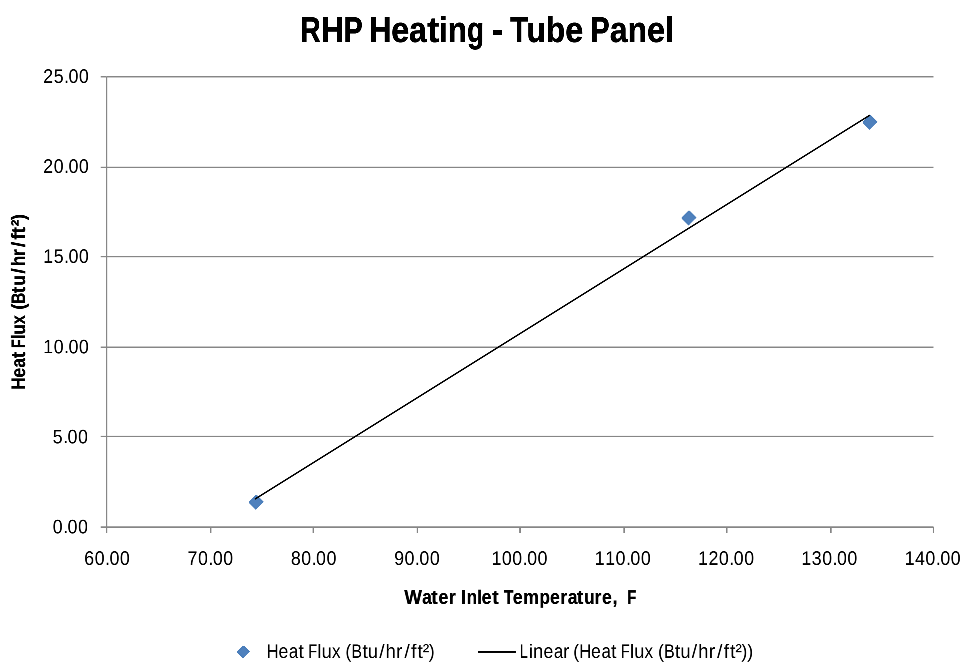

Figure 20 Effect of Water Inlet Temperature on Heat Flux for the Tube Panel in Radiant Heating Mode

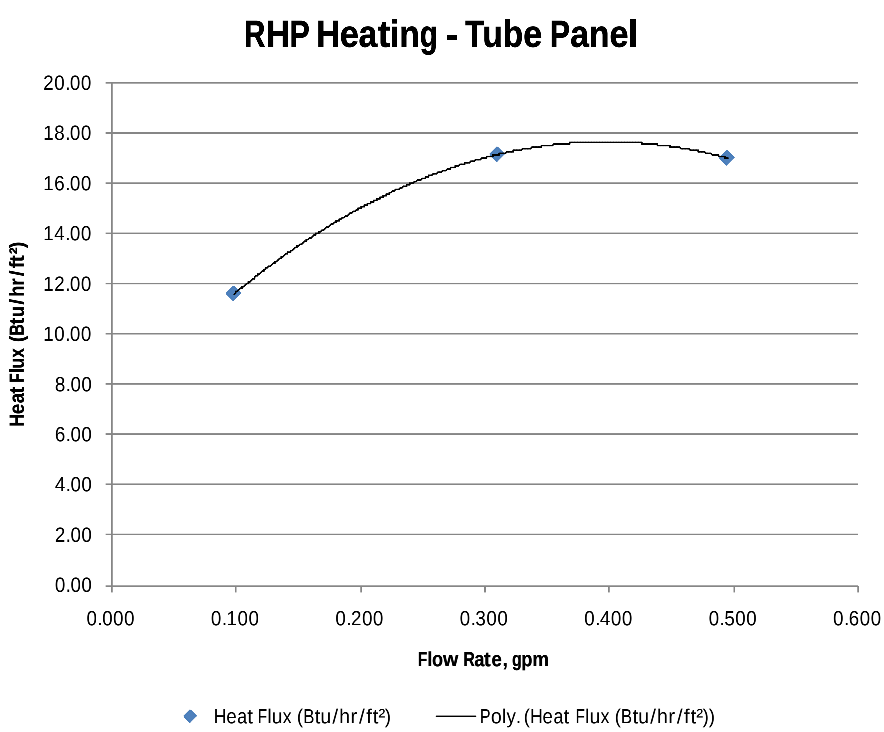

Figure 21 Effect of Flow Rate on Heat Flux for the Tube Panel in Radiant Heating Mode

In the cooling mode, flow rate is the most significant factor, followed by room temperature and then water inlet temperature. At 0.5 gpm and 58 F delivered water temperature, the heat flux is -10 to -12 Btu/hr/ft^2 (absorbed heat is negative) at a 78 degree room temperature. That equals -340 to -408 Btu/hr for a 34 sq. ft. panel.

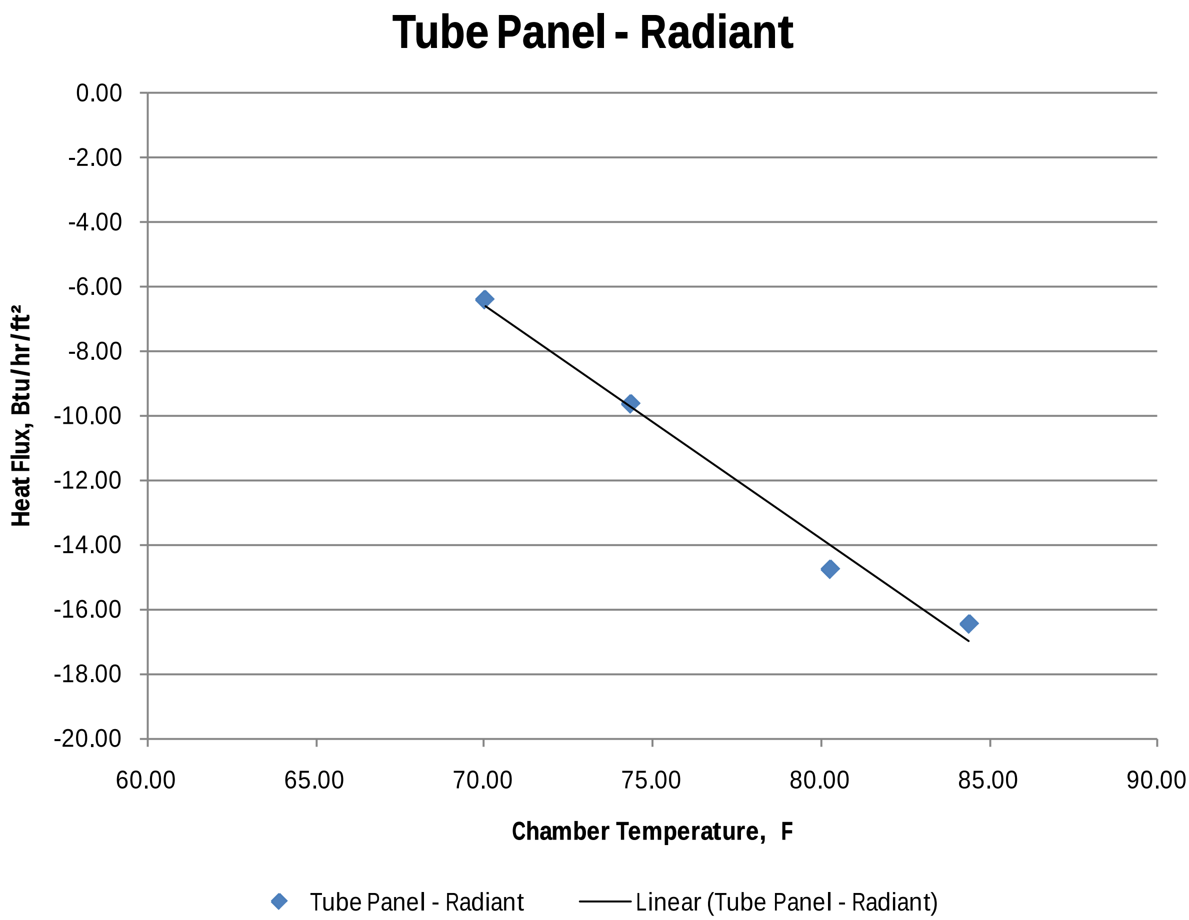

Figure 22 Radiant Cooling Performance for the Tube Panel With Varying Room Temperatures

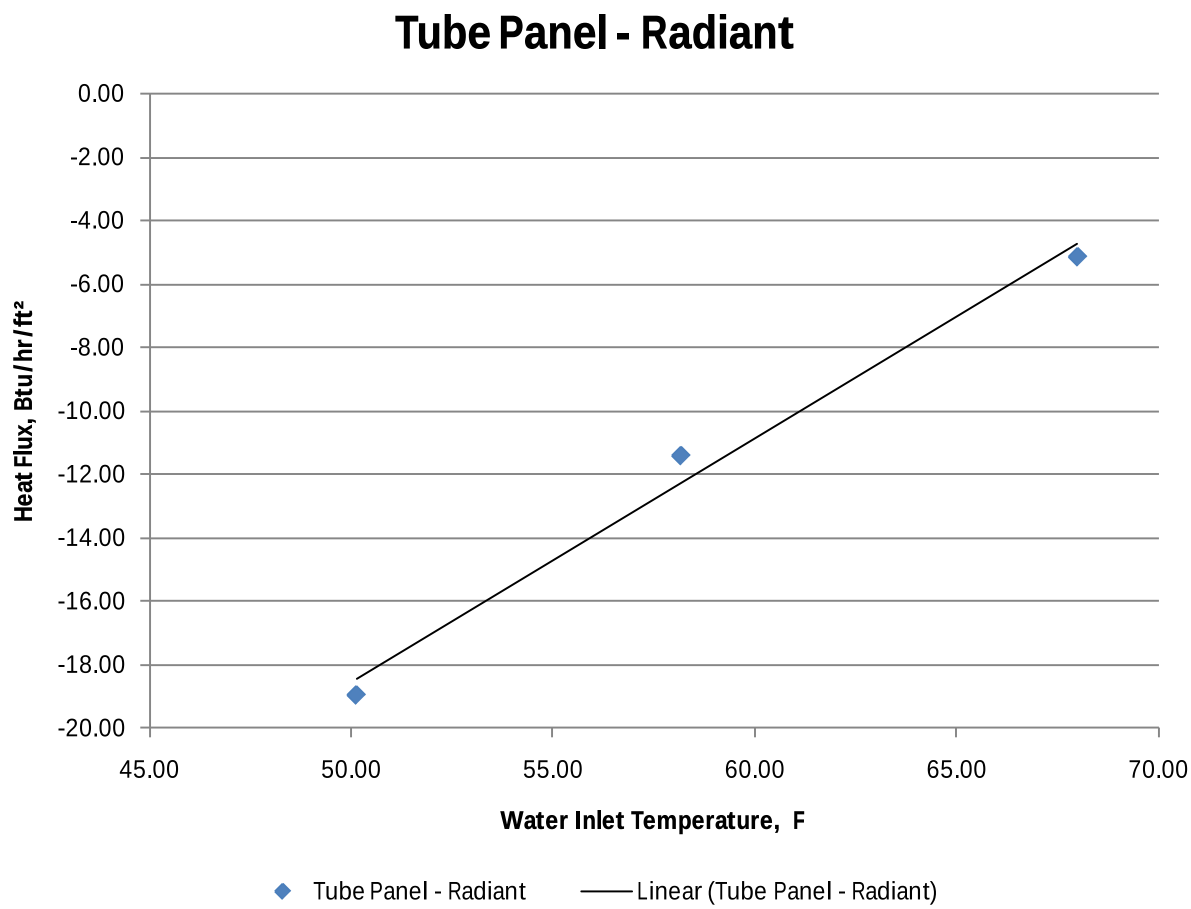

Figure 23 Radiant Cooling Results for the Tube Panel with Varying Water Inlet Temperature

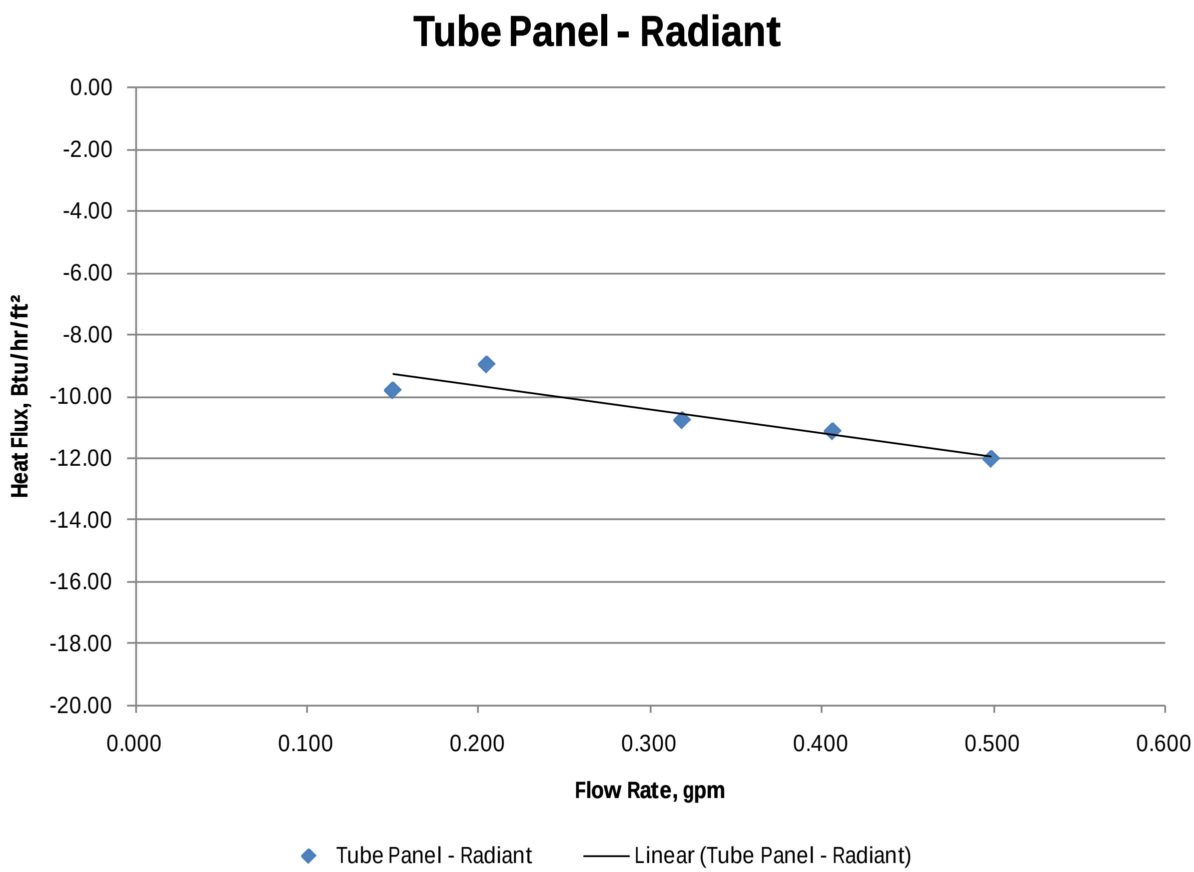

Figure 24 Radiant Cooling Heat Flux for Tube Panel with Varying Water Flow Rate

A pure radiant environment is not likely in residential homes and some air flow can have a beneficial heat transfer affect. Several tests were done on the heating performance of the tube panel with air flow of 100 cfm from the Sanyo mini-split fan operating on low speed. The results show heating capacity can be increased from 17 to 25 Btu/hr/ft^2 or about 50% when compared to the nominal value at 120 ^{O}F delivered water temperature at 0.3 gpm and a chamber temperature of 68 ^{O}F.

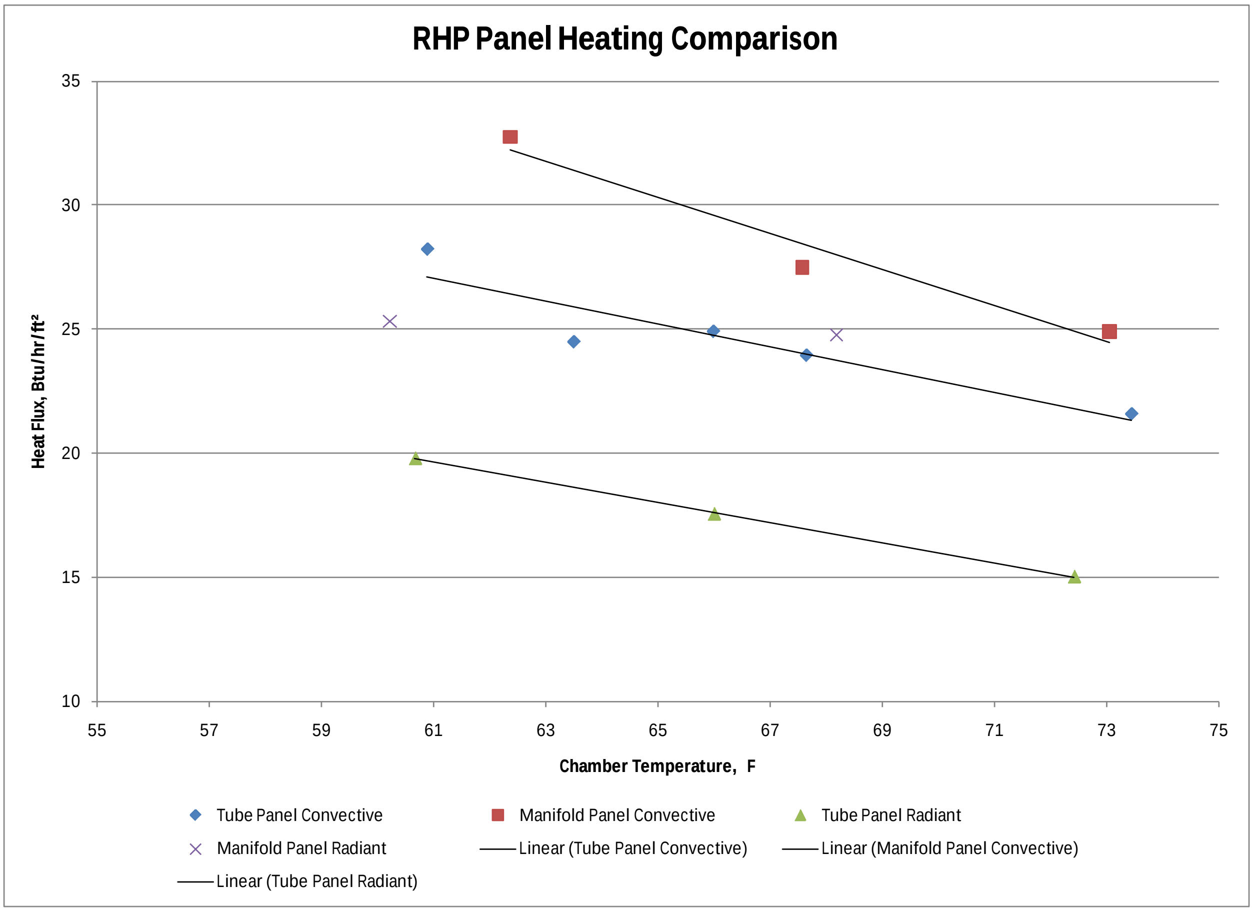

Figure 25 Convective vs. Radiant Heating Performance

Finally, the stratification tests show very even room temperature in a purely radiant environment with slight variation at the floor and at the ceiling. The radiant heating case shows the most increase above 7 ft. from the floor, rising 4 to 6 degrees. With some convective air flow, it is anticipated that this variation will be reduced. Figure 26, below, shows this variation.

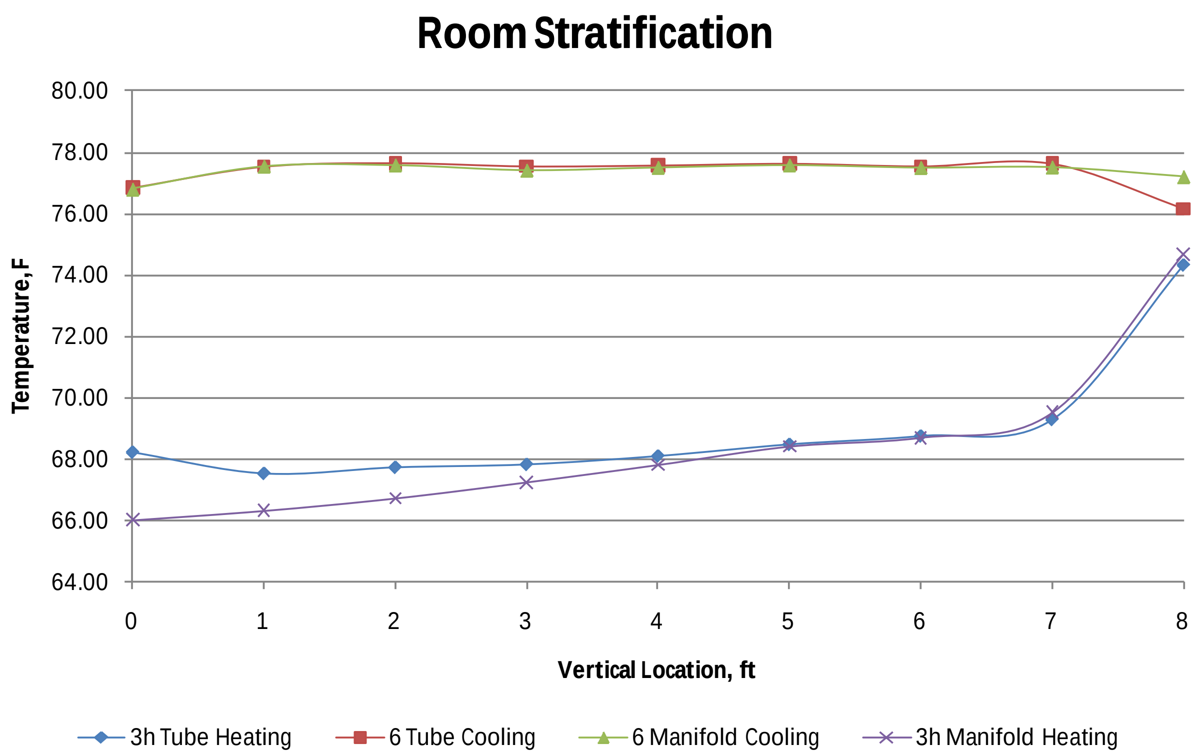

Figure 26 Temperature Stratification With Radiant Panels

Results and Conclusions

The radiant panels performed well in the laboratory testing. The heat flux on the heating and cooling season tests fell in line with expectations and some increases in flow rate can improve panel performance at the expense of pumping power. Results for each of the major test scenarios are provided in detail in the discussion section above.

For the radiant heating tests, the performance of the panel was most strongly dependant on the delivered water temperature, then the chamber temperature, then the flow rate. The flow rate is significant up to 0.3 gpm and then levels off. At 0.3 gpm and 120 F delivered water temperature, expect 15 – 17 Btu/hr/ft^2 heat flux or 510 to 600 Btu/hr for a 34 sq ft panel.

In the cooling mode, flow rate is the most significant factor, followed by room temperature and then water inlet temperature. At 0.5 gpm and 58 F delivered water temperature, the heat flux is -10 to -12 Btu/hr/ft^2 (absorbed heat is negative) at a 78 degree room temperature. That equals -340 to -408 Btu/hr for a 34 sq. ft. panel.

A pure radiant environment is not likely in residential homes and some air flow can have a beneficial heat transfer affect. Several tests were done on the heating performance of the tube panel with air flow of 100 cfm from the Sanyo mini-split fan operating on low speed. The results show heating capacity can be increased from 17 to 25 Btu/hr/ft^2 or about 50% when compared to the nominal value at 120 ^{O}F delivered water temperature at 0.3 gpm and a chamber temperature of 68 ^{O}F.

Finally, the stratification tests show very even room temperature in a purely radiant environment with slight variation at the floor and at the ceiling. The radiant heating case shows the most increase above 7 ft. from the floor, rising 4 to 6 degrees. With some convective air flow, it is anticipated that this variation will be reduced.

The conclusions of this project are that the radiant panels have an acceptable heating and cooling heat flux capacity for field testing, but the manifold panel has design-related drawbacks that make it an unacceptable candidate for the field. The tube panel produced an average heat flux of 16 Btu/hr/ft^2 for the heating season and absorbed 11 Btu/hr/ft^2 in the cooling season at nominal design conditions. Increasing the water flow rate or modifying the delivered water temperature both increase system capacity at the cost of requiring larger chilled water storage volume or colder chilled water temperature and higher pumping power costs. Higher heating season capacity can be achieved by increasing the hot water flow rate or temperature up to the limit of the water heater capabilities. Using these techniques, the heating season heat flux can be increased to 22 Btu/hr/ft^2 and cooling season heat flux can be increased to 18 Btu/hr/ft^2. Adding a convective element (100 cfm fan) in a room increases capacity up to 50% for heating when starting with nominal conditions and should have a similar beneficial effect for cooling.