Supplementary data: convection versus angle

These are supplementary data graphs to accompany *Natural Convection Heat Transfer from an Isothermal Plate* by Aubrey Jaffer. These measurements were made on the Convection Machine described in *Convection Measurement Apparatus and Methodology* by Aubrey Jaffer, which is available from:

`http://people.csail.mit.edu/jaffer/convect/`

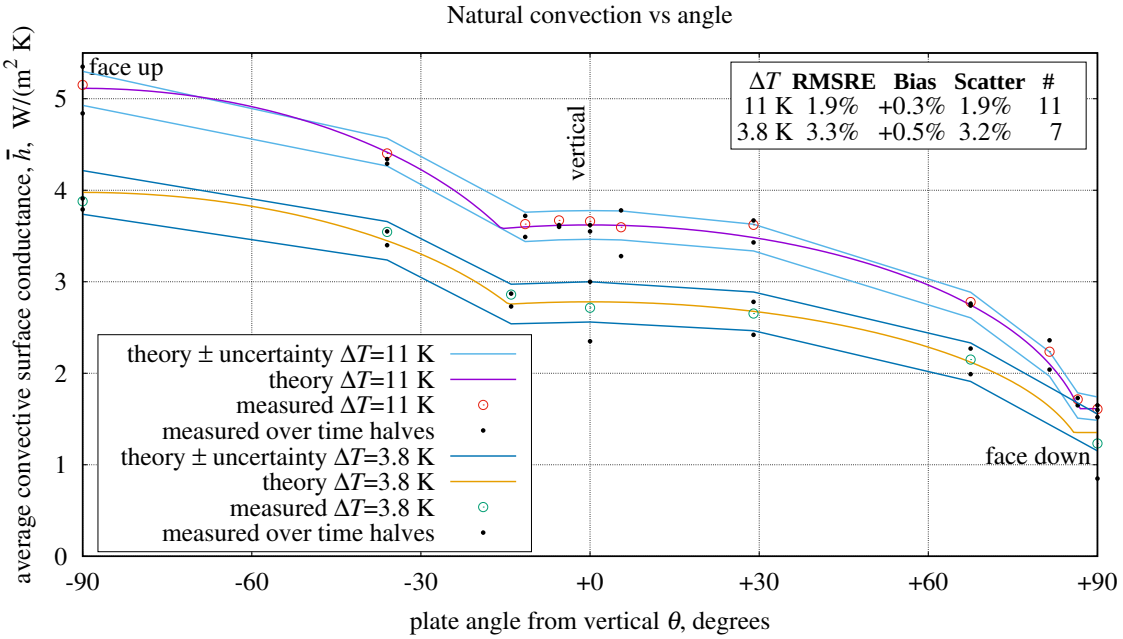
The apparatus measures convection by heating the plate, then sampling its decaying temperature every second for 6142 s. The plate is never in thermal equilibrium during a run.

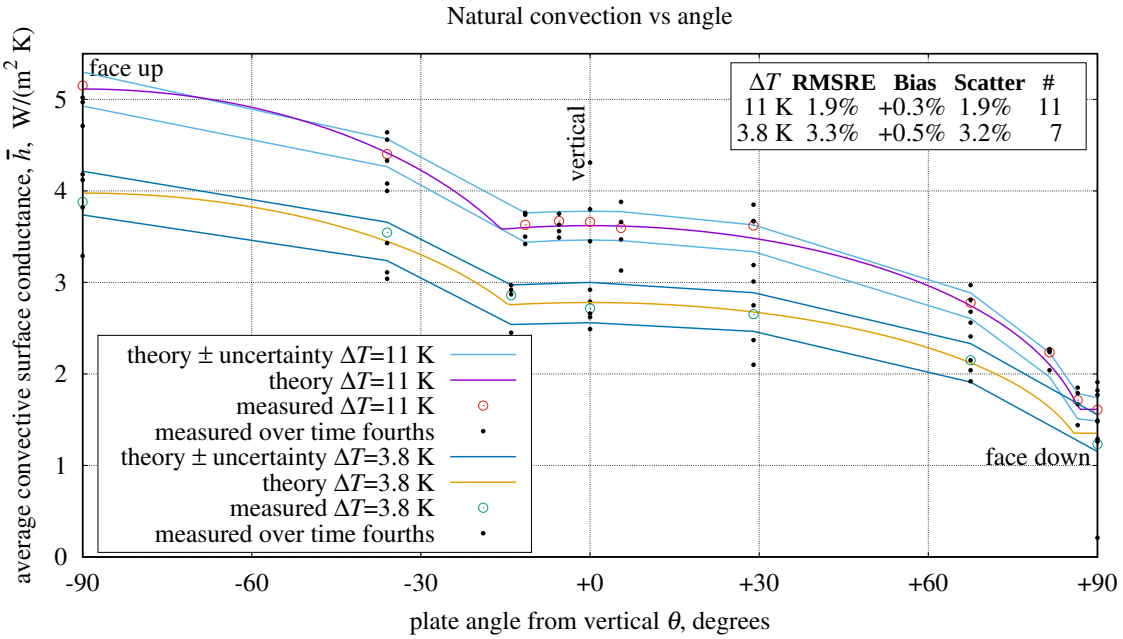
The first two graphs are of the average (not local) convection from each run along with their expected measurement uncertainties and theoretical predictions.

In the temperature versus time graphs the green, blue, and black traces are the plate, (insulated) back, and ambient temperatures respectively. The upper red trace is a simulation of the plate temperature with the back and ambient temperatures as inputs. The middle red trace is a simulation of the back temperature with the plate and ambient temperatures as inputs. The lower red line is the ambient temperature averaged over the measurement period.

The diamonds on the plate temperature trace mark the beginning and end of the measurement period, the ending temperature difference with ambient being at most half of the peak temperature difference with ambient.

Underneath each temperature graph is a graph of the plate's Rayleigh number versus time.


Natural convection vs angle
face up
vertical
face down
ΔT RMSRE Bias Scatter #
11 K 1.9% +0.3% 1.9% 11
3.8 K 3.3% +0.5% 3.2% 7
theory ± uncertainty ΔT=11 K
theory ΔT=11 K
measured ΔT=11 K
measured over time halves
theory ± uncertainty ΔT=3.8 K
theory ΔT=3.8 K
measured ΔT=3.8 K
measured over time halves
average convective surface conductance, h̄, W/(m2 K)
plate angle from vertical θ, degrees
-90
-60
-30
+0
+30
+60
+90
0
1
2
3
4
5


Natural convection vs angle
face up
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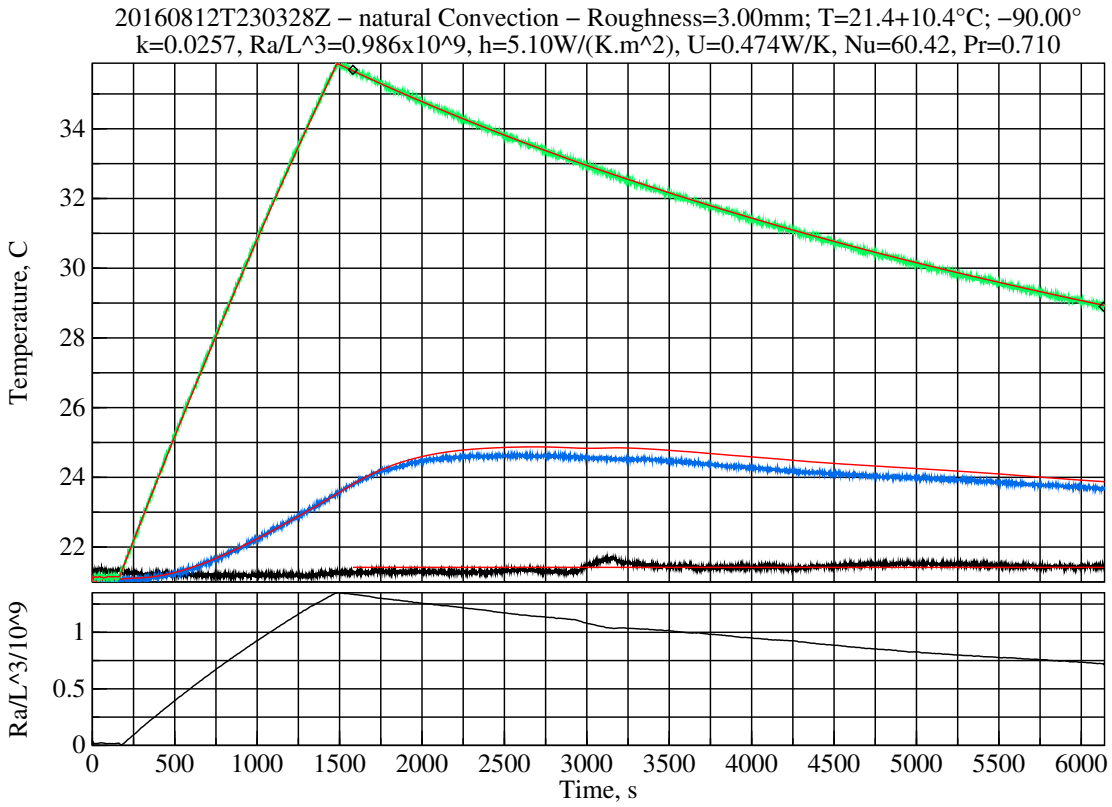
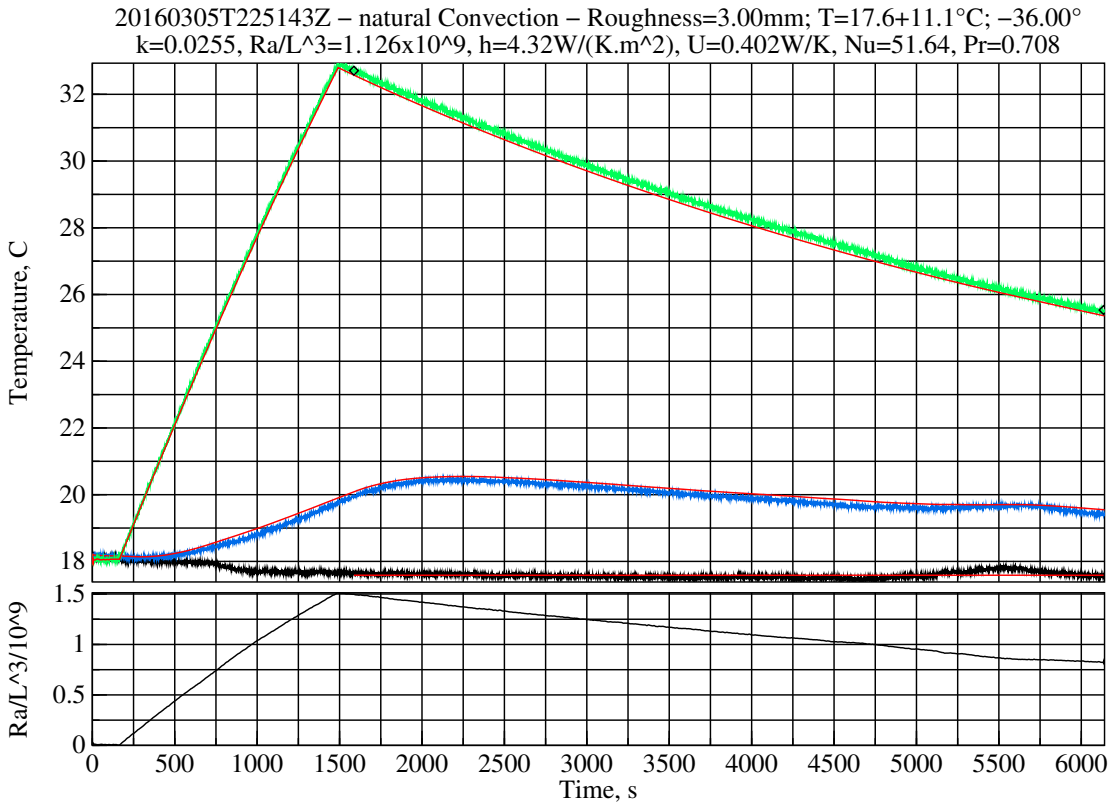
3.8 K 3.3% +0.5% 3.2% 7
theory ± uncertainty ΔT=11 K
theory ΔT=11 K
measured ΔT=11 K
measured over time fourths
theory ± uncertainty ΔT=3.8 K
theory ΔT=3.8 K
measured ΔT=3.8 K
measured over time fourths
average convective surface conductance, h̄, W/(m2 K)
plate angle from vertical θ, degrees
-90
-60
-30
+0
+30
+60
+90
0
1
2
3
4
5



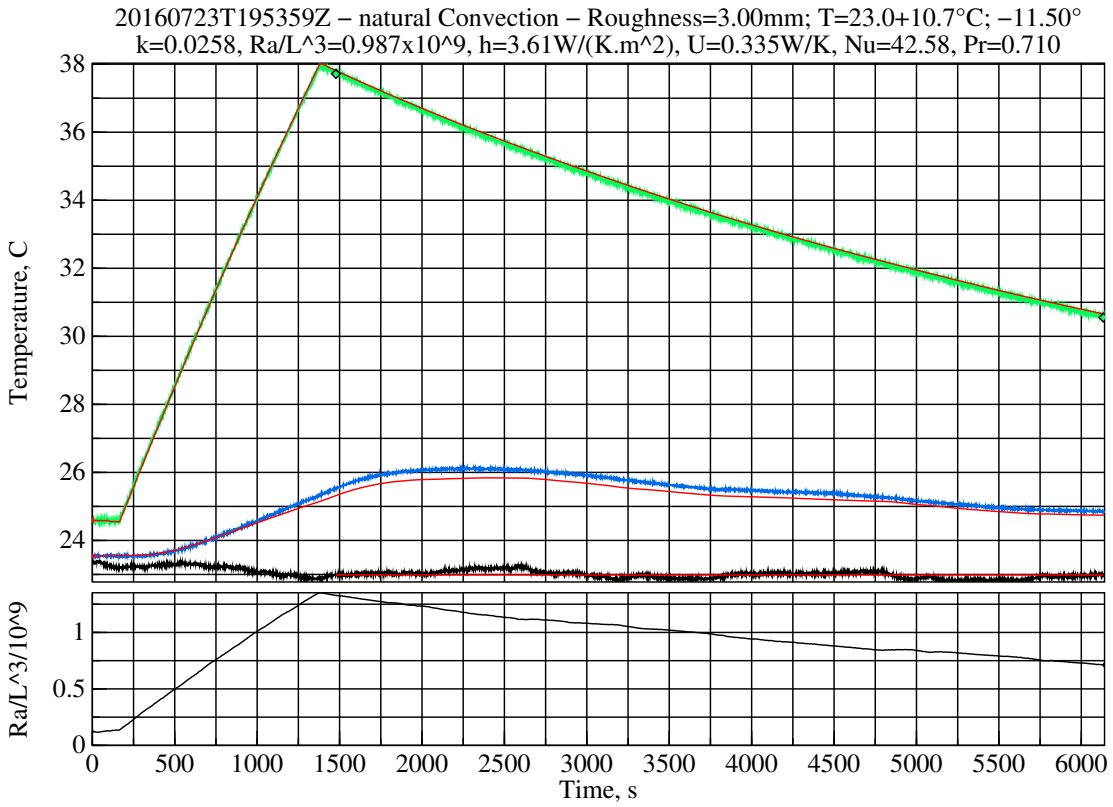
Estimated measurement uncertainties of natural convection at $\theta = -90.0$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	10.4K	+15.6%/K	0.10K	1.56%	LM35C differential
P	100kPa	+0.0005%/Pa	1.5kPa	0.79%	MPXH6115A6U air pressure
C_{pt}	4.69kJ/K	+0.029%/(J/K)	47J/K	1.36%	plate thermal capacity
C_S	1.000	−38.8%	0.050	1.94%	side reuptake
C_B	1.000	−10.7%	0.100	1.07%	back reuptake
L_c	0.305m	+420%/m	500um	0.21%	characteristic length
L_m	3.57mm	+826%/m	500um	0.41%	side metal strip width
ϵ_{XPS}	0.515	+25.0%	0.010	0.25%	XPS emissivity
ϵ_{tp}	0.890	+30.2%	0.015	0.45%	tape emissivity
Ω_{tp}	0.540	+20.4%	0.020	0.41%	tape coverage
ϵ_{rs}	0.040	+109%	0.010	1.09%	test-surface emissivity
ϵ_{wt}	0.900	+49.0%	0.025	1.23%	wind-tunnel emissivity
				3.63%	combined bias uncertainty



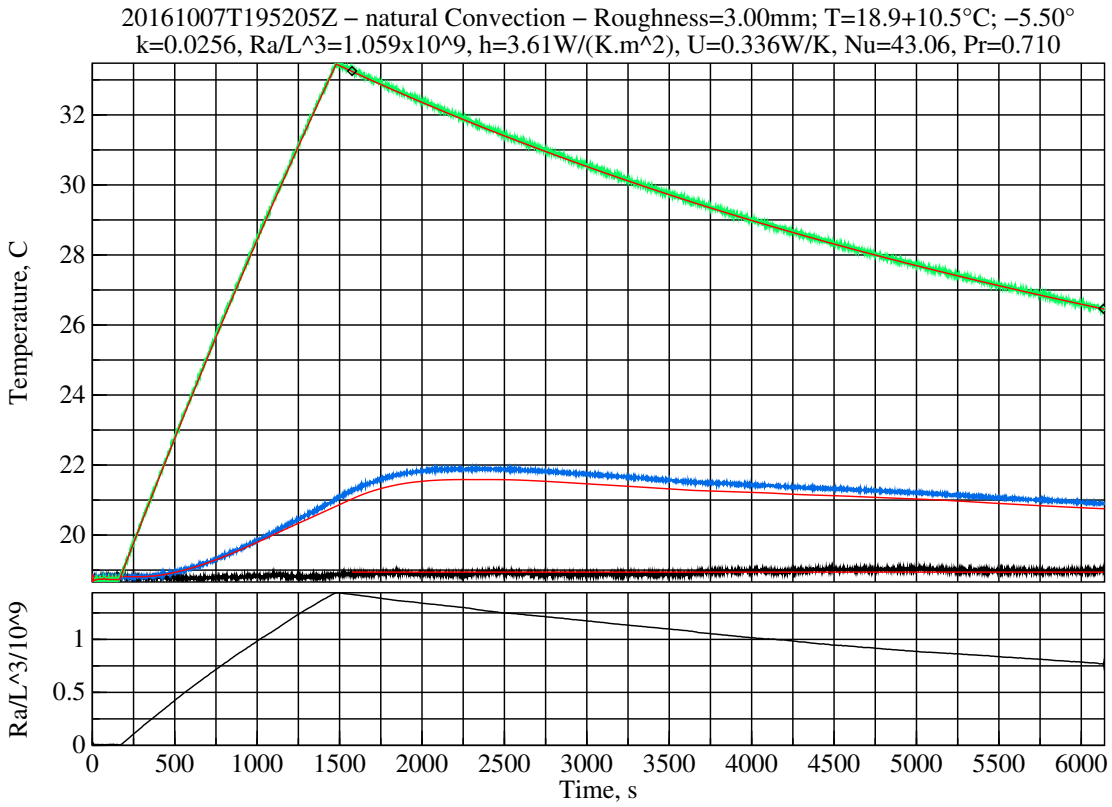
Estimated measurement uncertainties of natural convection at $\theta = -36.0$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	11.1K	+17.3%/K	0.10K	1.73%	LM35C differential
P	101kPa	+0.0006%/Pa	1.5kPa	0.87%	MPXH6115A6U air pressure
C_{pt}	4.69kJ/K	+0.035%/(J/K)	47J/K	1.62%	plate thermal capacity
C_S	1.000	−19.5%	0.050	0.98%	side reuptake
C_B	1.000	−4.60%	0.100	0.46%	back reuptake
L_c	0.305m	+480%/m	500um	0.24%	characteristic length
D_{PIR}	25.4mm	−268%/m	1.0mm	0.27%	insulation thickness
L_m	3.57mm	+902%/m	500um	0.45%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.259\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	0.29%	PIR thermal conductivity
ϵ_{XPS}	0.515	+27.2%	0.010	0.27%	XPS emissivity
ϵ_{tp}	0.890	+32.9%	0.015	0.49%	tape emissivity
Ω_{tp}	0.540	+22.2%	0.020	0.44%	tape coverage
ϵ_{rs}	0.040	+119%	0.010	1.19%	test-surface emissivity
ϵ_{wt}	0.900	+53.7%	0.025	1.34%	wind-tunnel emissivity
				3.43%	combined bias uncertainty



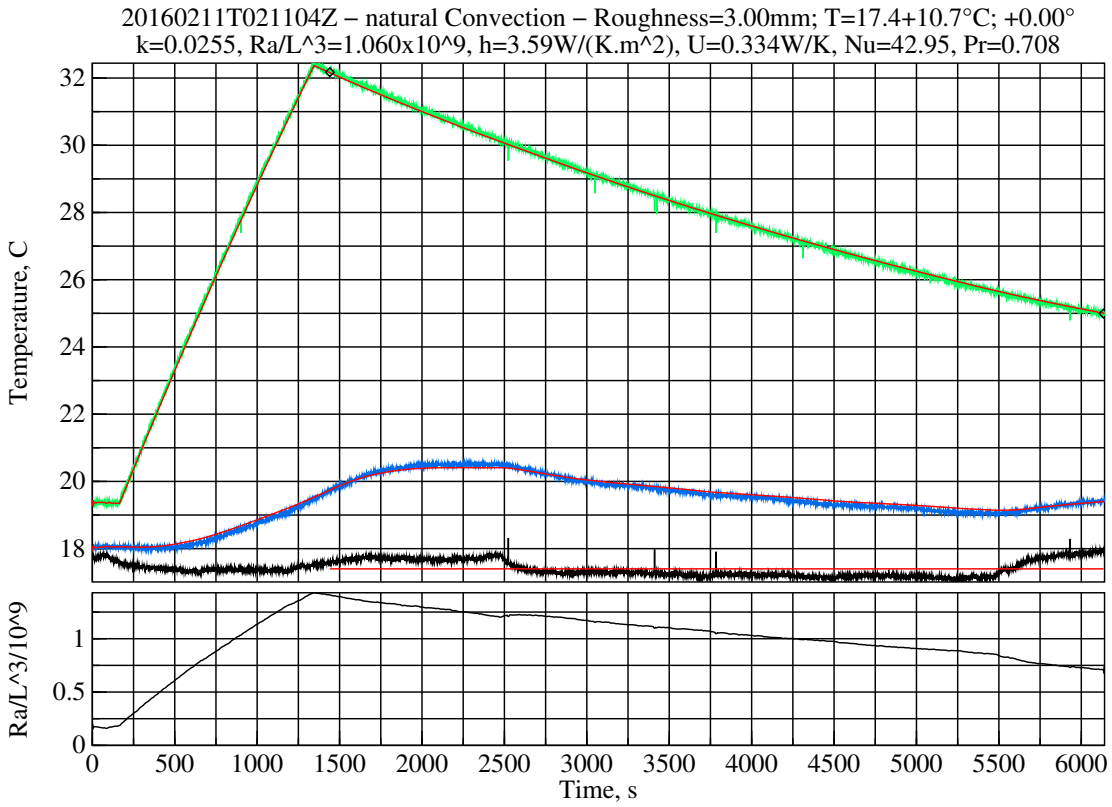
Estimated measurement uncertainties of natural convection at $\theta = -11.5$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	10.7K	+21.9%/K	0.10K	2.19%	LM35C differential
P	99.9kPa	+0.0007%/Pa	1.5kPa	1.03%	MPXH6115A6U air pressure
C_{pt}	4.69kJ/K	+0.043%/(J/K)	47J/K	2.01%	plate thermal capacity
C_V	1.000	−14.0%	0.100	1.40%	vertical reuptake
L_c	0.305m	+612%/m	500um	0.31%	characteristic length
D_{PIR}	25.4mm	−500%/m	1.0mm	0.50%	insulation thickness
D_g	1.00mm	−507%/m	500um	0.25%	air gap
L_m	3.57mm	+1172%/m	500um	0.59%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.483\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	0.54%	PIR thermal conductivity
ϵ_{XPS}	0.515	+37.2%	0.010	0.37%	XPS emissivity
ϵ_{tp}	0.890	+44.7%	0.015	0.67%	tape emissivity
Ω_{tp}	0.540	+30.3%	0.020	0.61%	tape coverage
ϵ_{rs}	0.040	+157%	0.010	1.57%	test-surface emissivity
ϵ_{wt}	0.900	+73.3%	0.025	1.83%	wind-tunnel emissivity
				4.45%	combined bias uncertainty



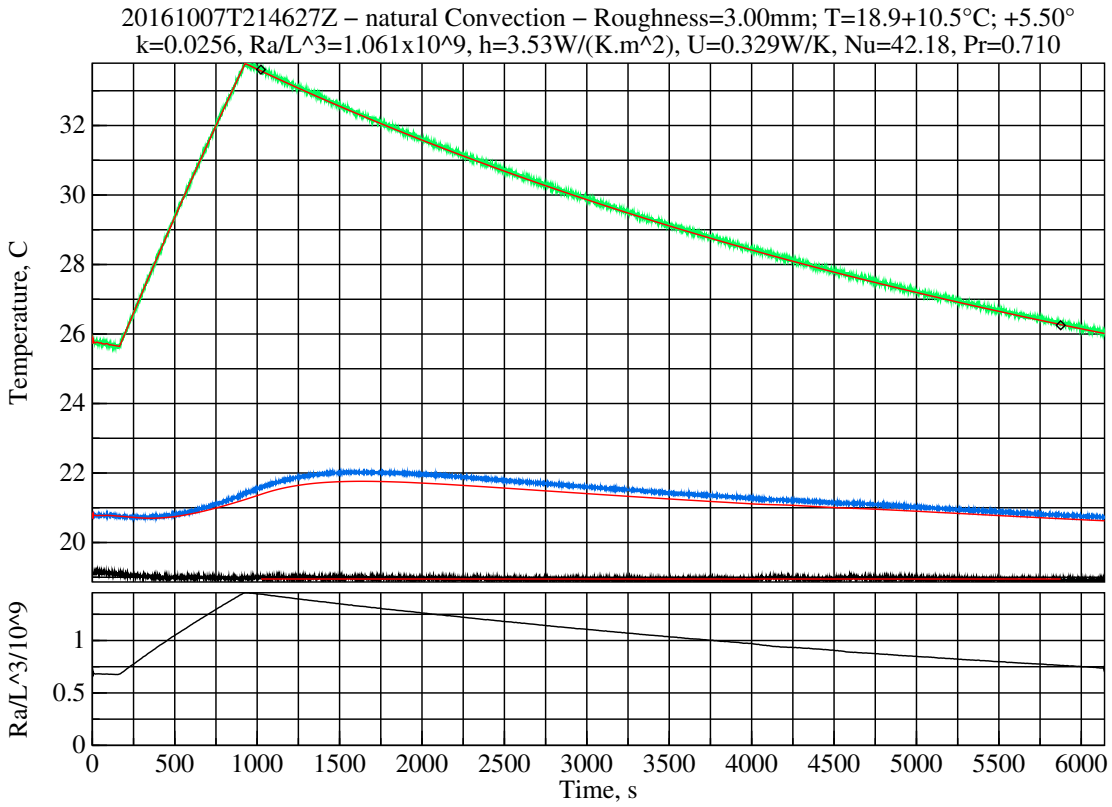
Estimated measurement uncertainties of natural convection at $\theta = -5.5$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	10.5K	+22.2%/K	0.10K	2.22%	LM35C differential
P	101kPa	+0.0007%/Pa	1.5kPa	1.03%	MPXH6115A6U air pressure
C_{pt}	4.69kJ/K	+0.042%/(J/K)	47J/K	1.98%	plate thermal capacity
C_V	1.000	−14.1%	0.100	1.41%	vertical reuptake
L_c	0.305m	+602%/m	500um	0.30%	characteristic length
D_{PIR}	25.4mm	−509%/m	1.0mm	0.51%	insulation thickness
D_g	1.00mm	−516%/m	500um	0.26%	air gap
L_m	3.57mm	+1107%/m	500um	0.55%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.492\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	0.55%	PIR thermal conductivity
ϵ_{XPS}	0.515	+35.1%	0.010	0.35%	XPS emissivity
ϵ_{tp}	0.890	+42.2%	0.015	0.63%	tape emissivity
Ω_{tp}	0.540	+28.6%	0.020	0.57%	tape coverage
ϵ_{rs}	0.040	+148%	0.010	1.48%	test-surface emissivity
ϵ_{wt}	0.900	+69.1%	0.025	1.73%	wind-tunnel emissivity
				4.36%	combined bias uncertainty



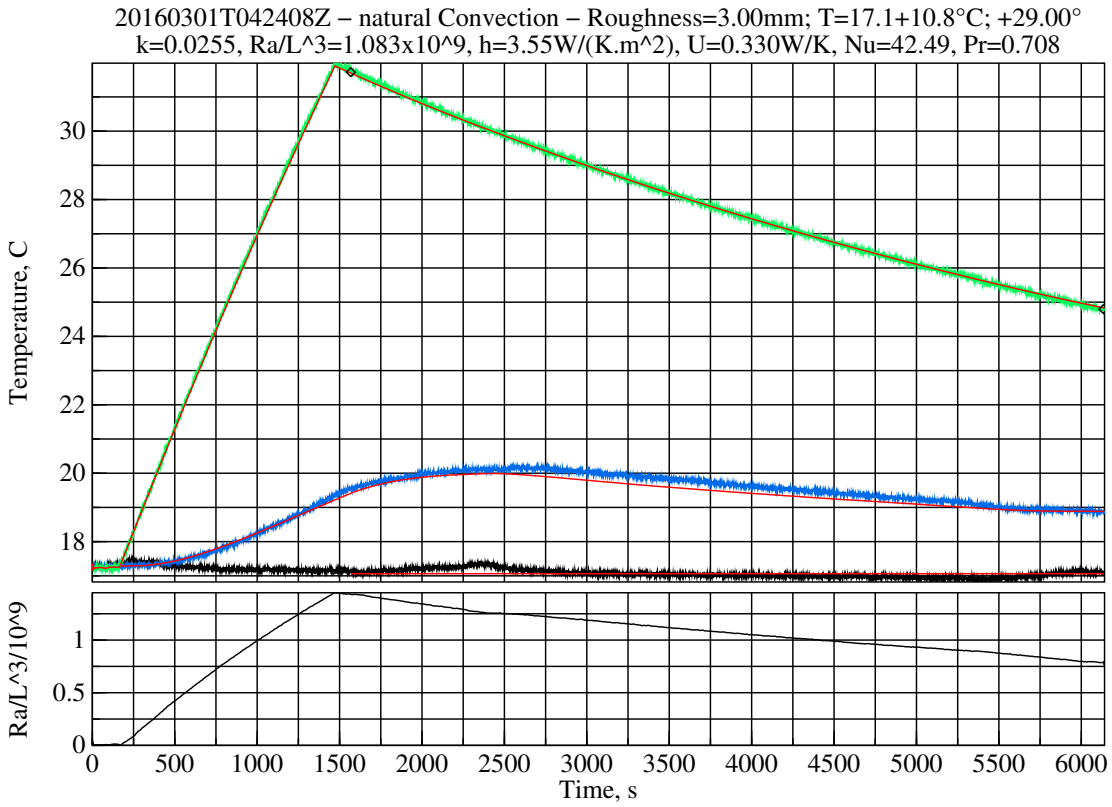
Estimated measurement uncertainties of natural convection at $\theta = 0.0$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	10.7K	+21.7%/K	0.10K	2.17%	LM35C differential
P	99.4kPa	+0.0007%/Pa	1.5kPa	1.05%	MPXH6115A6U air pressure
C_{pt}	4.69kJ/K	+0.042%/(J/K)	47J/K	1.98%	plate thermal capacity
C_V	1.000	−14.2%	0.100	1.42%	vertical reuptake
L_c	0.305m	+598%/m	500um	0.30%	characteristic length
D_{PIR}	25.4mm	−513%/m	1.0mm	0.51%	insulation thickness
D_g	1.00mm	−520%/m	500um	0.26%	air gap
L_m	3.57mm	+1090%/m	500um	0.54%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.496\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	0.55%	PIR thermal conductivity
ϵ_{XPS}	0.515	+34.8%	0.010	0.35%	XPS emissivity
ϵ_{tp}	0.890	+41.9%	0.015	0.63%	tape emissivity
Ω_{tp}	0.540	+28.4%	0.020	0.57%	tape coverage
ϵ_{rs}	0.040	+147%	0.010	1.47%	test-surface emissivity
ϵ_{wt}	0.900	+68.6%	0.025	1.71%	wind-tunnel emissivity
				4.33%	combined bias uncertainty



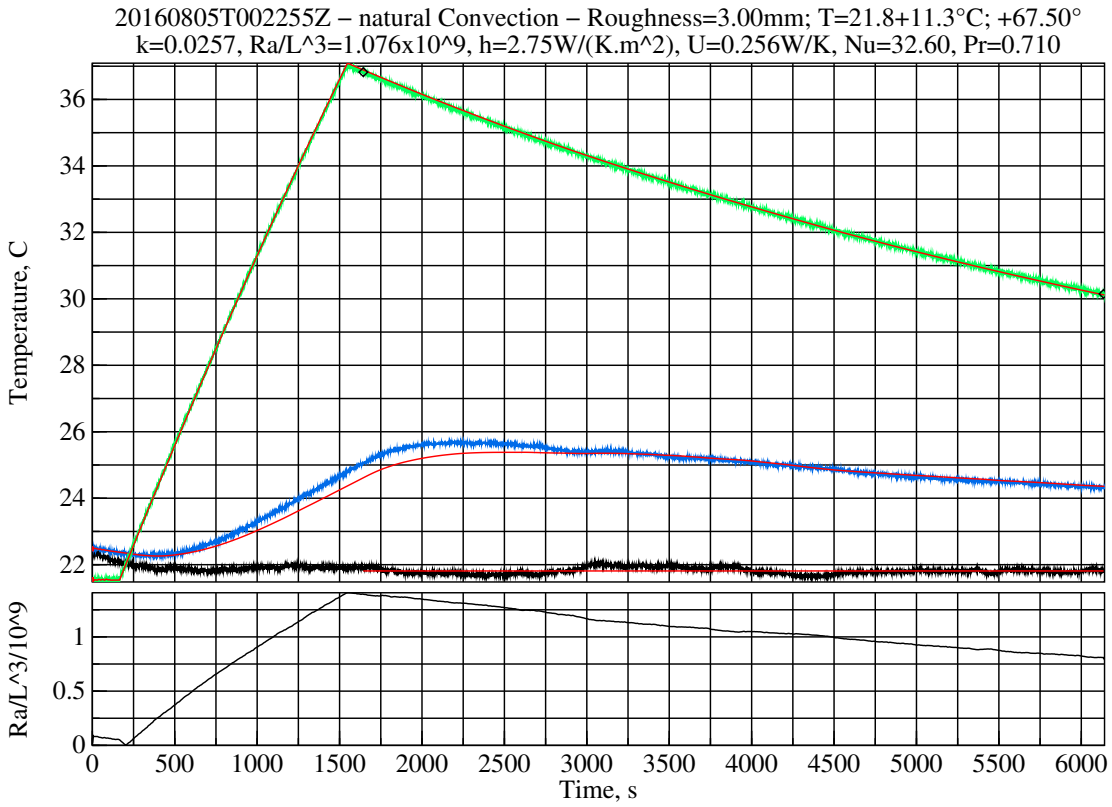
Estimated measurement uncertainties of natural convection at $\theta = 5.5$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	10.5K	+22.4%/K	0.10K	2.24%	LM35C differential
P	102kPa	+0.0007%/Pa	1.5kPa	1.04%	MPXH6115A6U air pressure
C_{pt}	4.69kJ/K	+0.043%/(J/K)	47J/K	2.00%	plate thermal capacity
C_V	1.000	−14.1%	0.100	1.41%	vertical reuptake
L_c	0.305m	+607%/m	500um	0.30%	characteristic length
D_{PIR}	25.4mm	−513%/m	1.0mm	0.51%	insulation thickness
D_g	1.00mm	−520%/m	500um	0.26%	air gap
L_m	3.57mm	+1108%/m	500um	0.55%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.496\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	0.55%	PIR thermal conductivity
ϵ_{XPS}	0.515	+35.1%	0.010	0.35%	XPS emissivity
ϵ_{tp}	0.890	+42.2%	0.015	0.63%	tape emissivity
Ω_{tp}	0.540	+28.6%	0.020	0.57%	tape coverage
ϵ_{rs}	0.040	+148%	0.010	1.48%	test-surface emissivity
ϵ_{wt}	0.900	+69.1%	0.025	1.73%	wind-tunnel emissivity
				4.39%	combined bias uncertainty



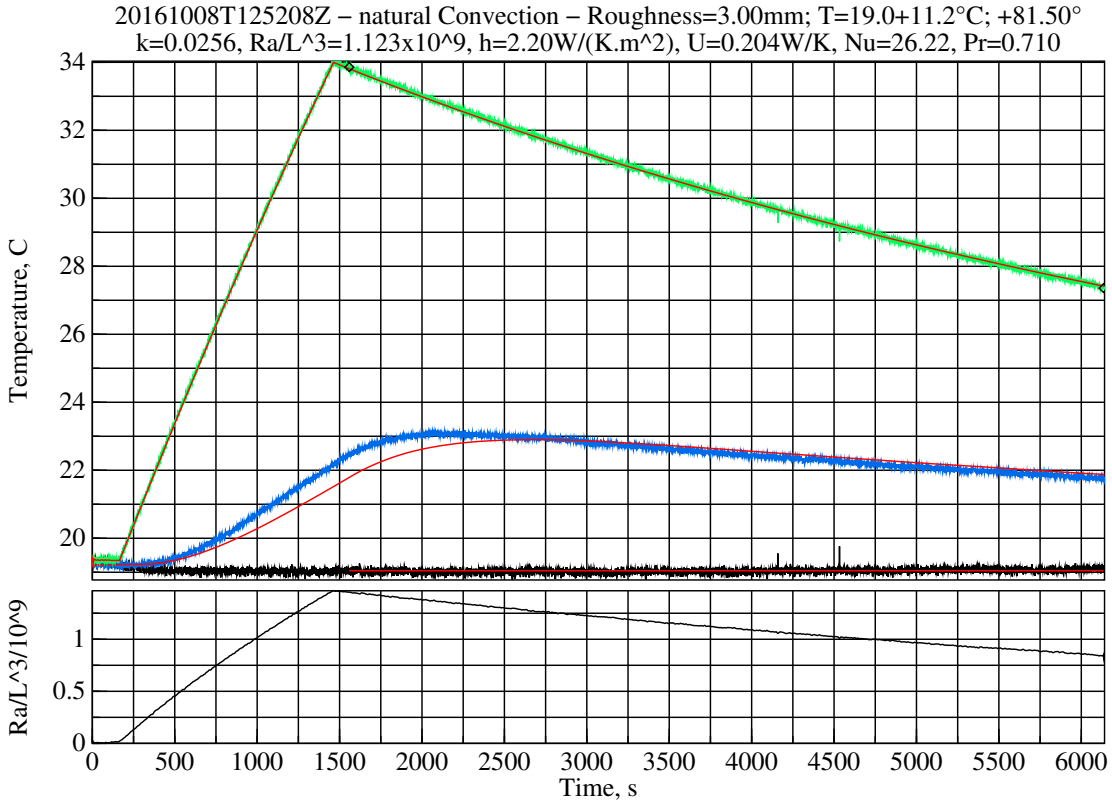
Estimated measurement uncertainties of natural convection at $\theta = 29.0$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	10.8K	+21.9%/K	0.10K	2.19%	LM35C differential
P	99.9kPa	+0.0007%/Pa	1.5kPa	1.05%	MPXH6115A6U air pressure
C_{pt}	4.69kJ/K	+0.043%/(J/K)	47J/K	2.01%	plate thermal capacity
C_V	1.000	−5.29%	0.100	0.53%	vertical reuptake
L_c	0.305m	+610%/m	500um	0.31%	characteristic length
D_{PIR}	25.4mm	−529%/m	1.0mm	0.53%	insulation thickness
D_g	1.00mm	−537%/m	500um	0.27%	air gap
L_m	3.57mm	+1145%/m	500um	0.57%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.512\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	0.57%	PIR thermal conductivity
ϵ_{XPS}	0.515	+34.8%	0.010	0.35%	XPS emissivity
ϵ_{tp}	0.890	+42.1%	0.015	0.63%	tape emissivity
Ω_{tp}	0.540	+28.4%	0.020	0.57%	tape coverage
ϵ_{rs}	0.040	+151%	0.010	1.51%	test-surface emissivity
ϵ_{wt}	0.900	+69.0%	0.025	1.73%	wind-tunnel emissivity
θ	29.0°	−0.408%/°	0.50°	0.20%	plate angle
				4.19%	combined bias uncertainty



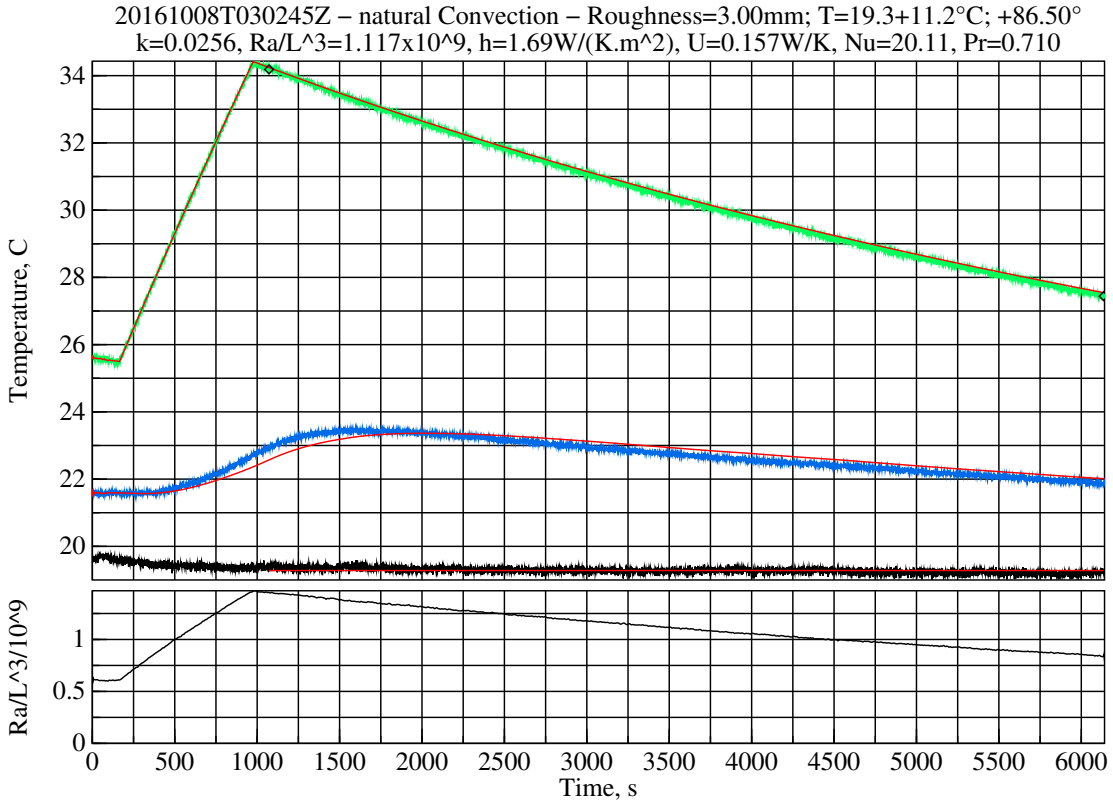
Estimated measurement uncertainties of natural convection at $\theta = 67.5$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	11.3K	+24.9%/K	0.10K	2.49%	LM35C differential
T_{bb}	295K	+0.407%/K	0.50K	0.20%	radiative temperature
P	101kPa	+0.0008%/Pa	1.5kPa	1.15%	MPXH6115A6U air pressure
C_{pt}	4.69kJ/K	+0.052%/(J/K)	47J/K	2.42%	plate thermal capacity
C_V	1.000	−3.37%	0.100	0.34%	vertical reuptake
L_c	0.305m	+741%/m	500um	0.37%	characteristic length
D_{PIR}	25.4mm	−568%/m	1.0mm	0.57%	insulation thickness
D_g	1.00mm	−576%/m	500um	0.29%	air gap
L_m	3.57mm	+1517%/m	500um	0.76%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.549\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	0.61%	PIR thermal conductivity
ϵ_{XPS}	0.515	+45.8%	0.010	0.46%	XPS emissivity
ϵ_{tp}	0.890	+55.3%	0.015	0.83%	tape emissivity
Ω_{tp}	0.540	+37.3%	0.020	0.75%	tape coverage
ϵ_{rs}	0.040	+200%	0.010	2.00%	test-surface emissivity
ϵ_{wt}	0.900	+91.8%	0.025	2.30%	wind-tunnel emissivity
θ	67.5°	−0.601%/°	0.50°	0.30%	plate angle
				5.09%	combined bias uncertainty



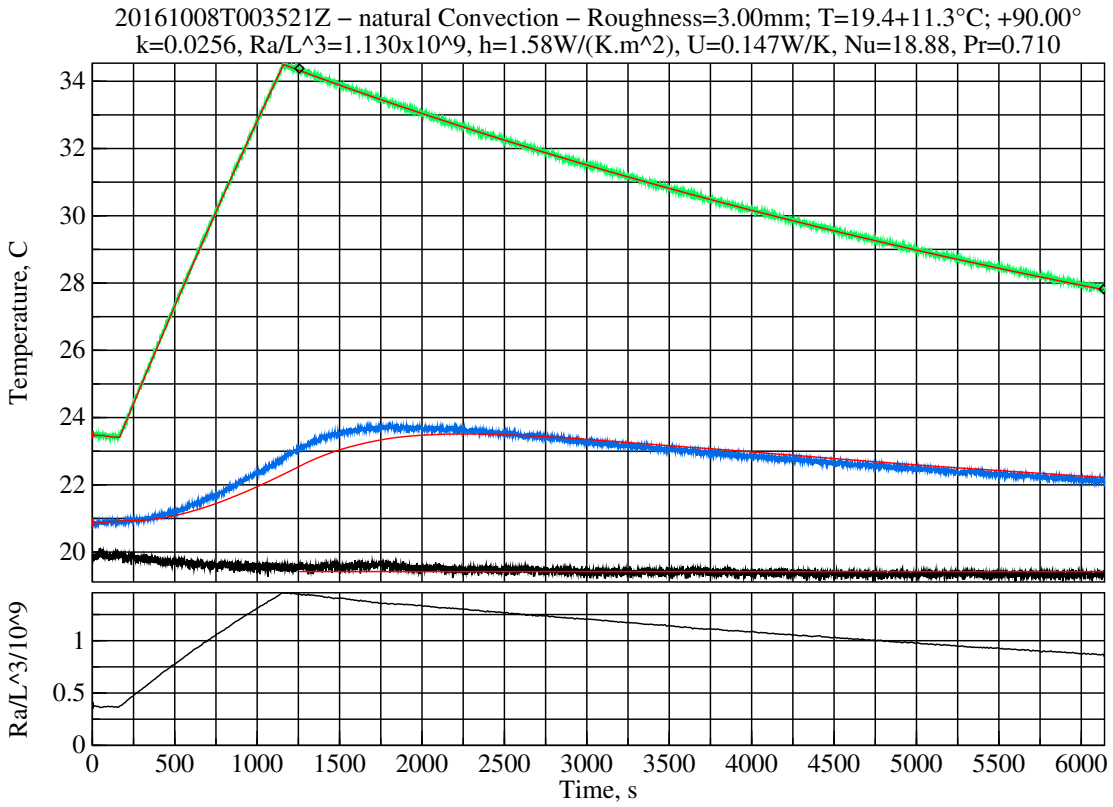
Estimated measurement uncertainties of natural convection at $\theta = 81.5$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	11.2K	+30.2%/K	0.10K	3.02%	LM35C differential
T_{bb}	292K	+0.521%/K	0.50K	0.26%	radiative temperature
P	101kPa	+0.0009%/Pa	1.5kPa	1.30%	MPXH6115A6U air pressure
C_{pt}	4.69kJ/K	+0.063%/(J/K)	47J/K	2.94%	plate thermal capacity
L_c	0.305m	+902%/m	500um	0.45%	characteristic length
D_{PIR}	25.4mm	−685%/m	1.0mm	0.69%	insulation thickness
D_g	1.00mm	−695%/m	500um	0.35%	air gap
L_m	3.57mm	+1925%/m	500um	0.96%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.663\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	0.74%	PIR thermal conductivity
ϵ_{XPS}	0.515	+57.6%	0.010	0.58%	XPS emissivity
ϵ_{tp}	0.890	+69.7%	0.015	1.04%	tape emissivity
Ω_{tp}	0.540	+46.9%	0.020	0.94%	tape coverage
ϵ_{rs}	0.040	+253%	0.010	2.53%	test-surface emissivity
ϵ_b	0.190	+15.7%	0.020	0.31%	back emissivity
ϵ_{wt}	0.900	+116%	0.025	2.91%	wind-tunnel emissivity
θ	81.5°	−2.28%/°	0.50°	1.14%	plate angle
				6.36%	combined bias uncertainty



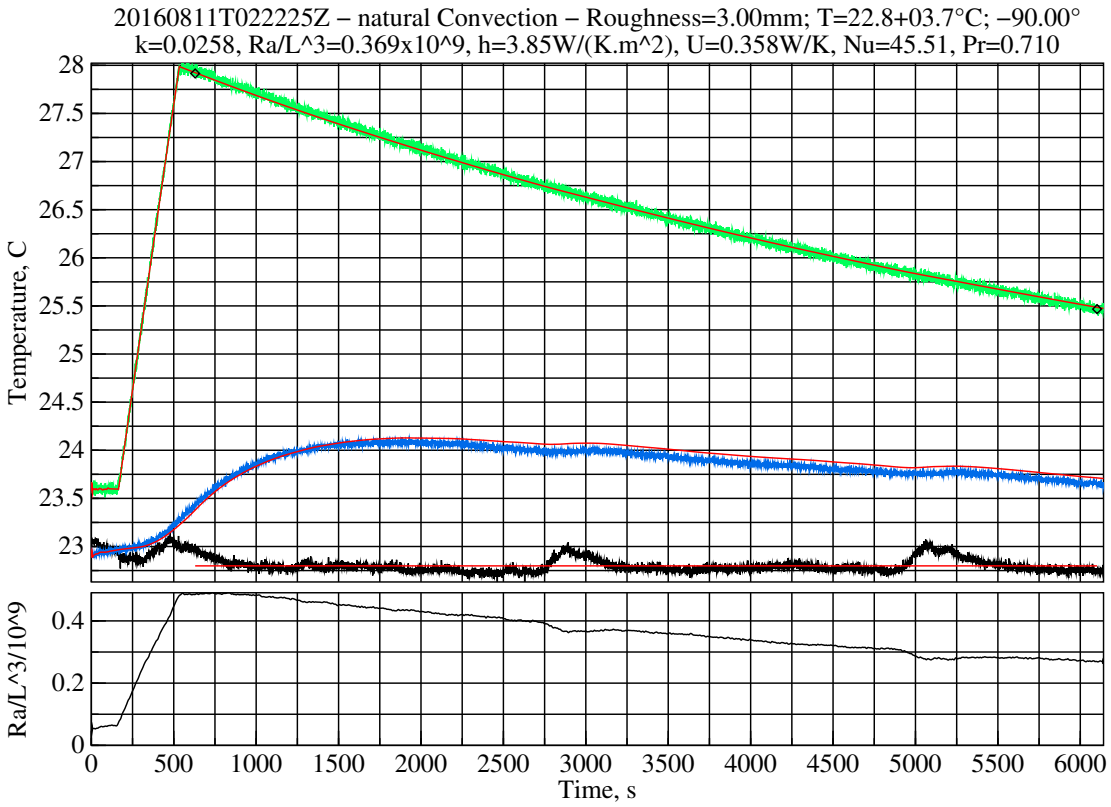
Estimated measurement uncertainties of natural convection at $\theta = 86.5$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
T	298K	+0.483%/K	0.50K	0.24%	LM35C temperature sensor
ΔT	11.2K	+36.2%/K	0.10K	3.62%	LM35C differential
T_{bb}	293K	+0.668%/K	0.50K	0.33%	radiative temperature
P	101kPa	+0.0010%/Pa	1.5kPa	1.45%	MPXH6115A6U air pressure
C_{pt}	4.69kJ/K	+0.075%/(J/K)	47J/K	3.54%	plate thermal capacity
L_c	0.305m	+1083%/m	500um	0.54%	characteristic length
D_{PIR}	25.4mm	−864%/m	1.0mm	0.86%	insulation thickness
D_g	1.00mm	−877%/m	500um	0.44%	air gap
L_m	3.57mm	+2463%/m	500um	1.23%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.836\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	0.93%	PIR thermal conductivity
ϵ_{XPS}	0.515	+73.7%	0.010	0.74%	XPS emissivity
ϵ_{tp}	0.890	+89.2%	0.015	1.34%	tape emissivity
Ω_{tp}	0.540	+60.1%	0.020	1.20%	tape coverage
ϵ_{rs}	0.040	+323%	0.010	3.23%	test-surface emissivity
ϵ_b	0.190	+21.0%	0.020	0.42%	back emissivity
ϵ_{wt}	0.900	+149%	0.025	3.73%	wind-tunnel emissivity
θ	86.5°	−6.48%/°	0.50°	3.24%	plate angle
				8.39%	combined bias uncertainty



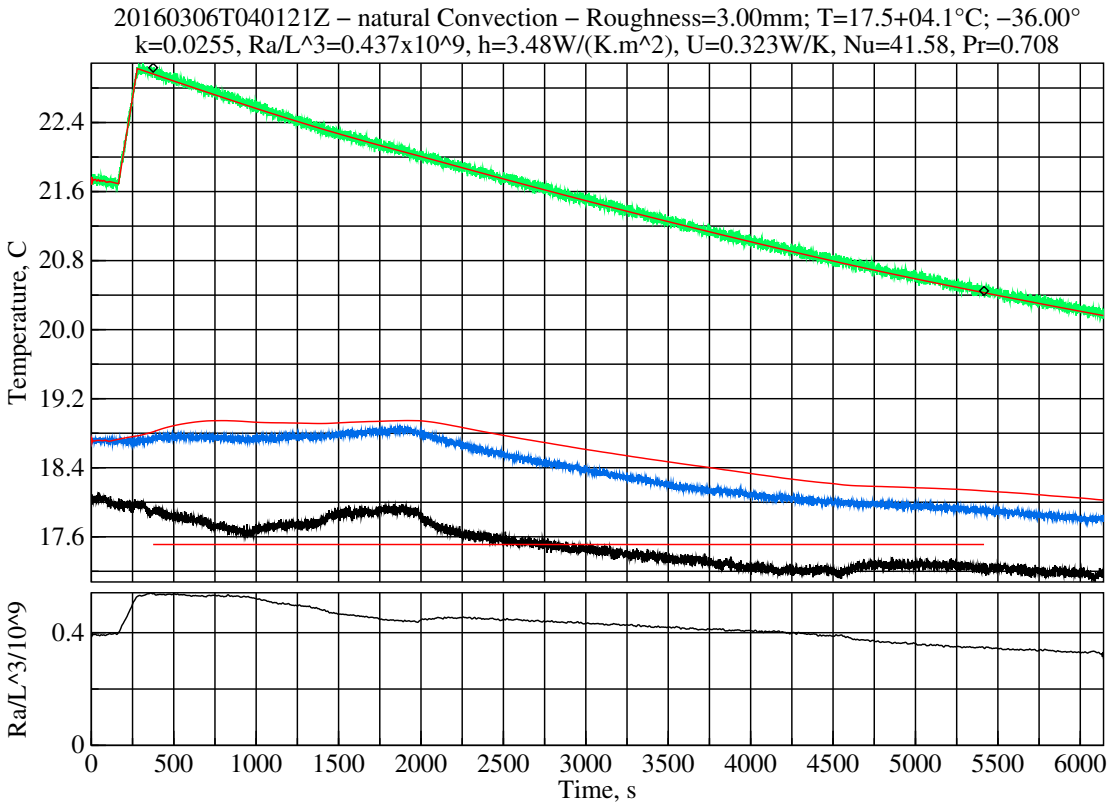
Estimated measurement uncertainties of natural convection at $\theta = 90.0$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
T	298K	+0.617%/K	0.50K	0.31%	LM35C temperature sensor
ΔT	11.3K	+36.3%/K	0.10K	3.63%	LM35C differential
T_{bb}	293K	+0.688%/K	0.50K	0.34%	radiative temperature
P	102kPa	+0.0008%/Pa	1.5kPa	1.27%	MPXH6115A6U air pressure
C_{pt}	4.69kJ/K	+0.078%/(J/K)	47J/K	3.66%	plate thermal capacity
L_c	0.305m	+1122%/m	500um	0.56%	characteristic length
D_{PIR}	25.4mm	−888%/m	1.0mm	0.89%	insulation thickness
D_g	1.00mm	−900%/m	500um	0.45%	air gap
L_m	3.57mm	+2539%/m	500um	1.27%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.858\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	0.95%	PIR thermal conductivity
ϵ_{XPS}	0.515	+76.0%	0.010	0.76%	XPS emissivity
ϵ_{tp}	0.890	+91.9%	0.015	1.38%	tape emissivity
Ω_{tp}	0.540	+61.9%	0.020	1.24%	tape coverage
ϵ_{rs}	0.040	+333%	0.010	3.33%	test-surface emissivity
ϵ_b	0.190	+21.7%	0.020	0.43%	back emissivity
ϵ_{wt}	0.900	+154%	0.025	3.84%	wind-tunnel emissivity
θ	90.0°	−1.05%/°	0.50°	0.53%	plate angle
				7.91%	combined bias uncertainty



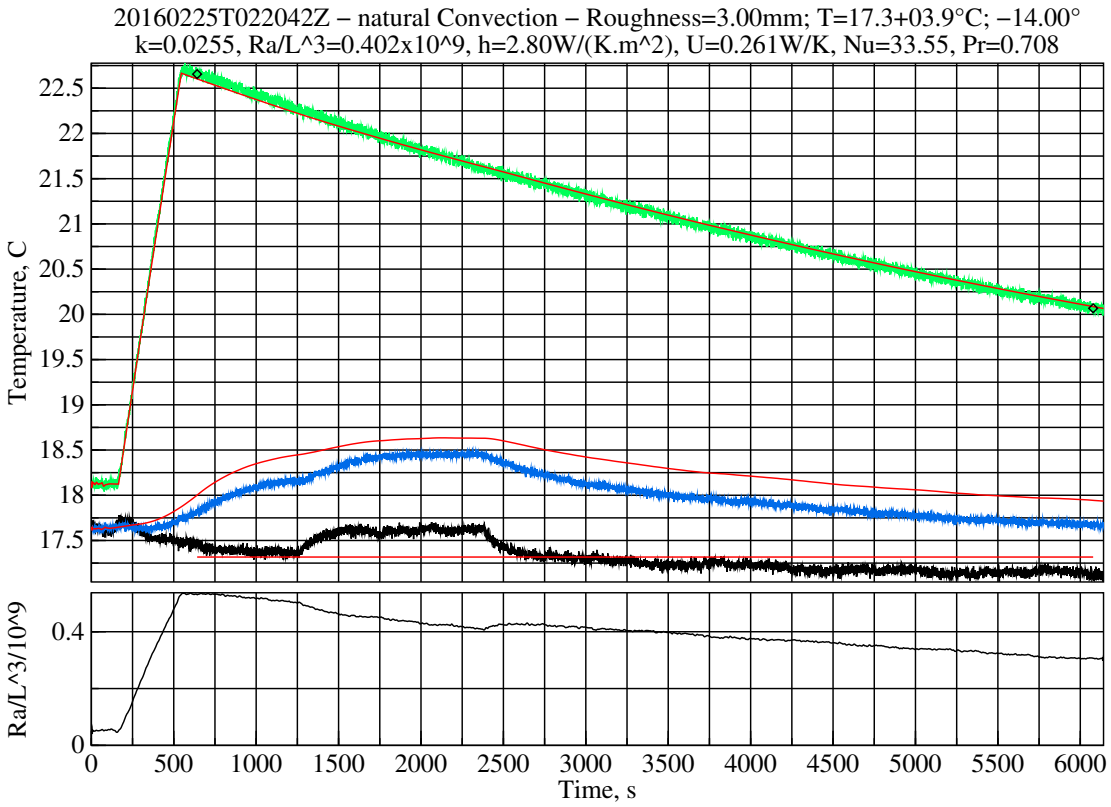
Estimated measurement uncertainties of natural convection at $\theta = -90.0$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	3.75K	+46.4%/K	0.10K	4.64%	LM35C differential
P	101kPa	+0.0005%/Pa	1.5kPa	0.75%	MPXH6115A6U air pressure
C_{pt}	4.69kJ/K	+0.032%/(J/K)	47J/K	1.49%	plate thermal capacity
C_S	1.000	−41.2%	0.050	2.06%	side reuptake
C_B	1.000	−13.6%	0.100	1.36%	back reuptake
L_c	0.305m	+456%/m	500um	0.23%	characteristic length
L_m	3.57mm	+1040%/m	500um	0.52%	side metal strip width
ϵ_{XPS}	0.515	+33.2%	0.010	0.33%	XPS emissivity
ϵ_{tp}	0.890	+39.9%	0.015	0.60%	tape emissivity
Ω_{tp}	0.540	+27.0%	0.020	0.54%	tape coverage
ϵ_{rs}	0.040	+140%	0.010	1.40%	test-surface emissivity
ϵ_{wt}	0.900	+64.6%	0.025	1.62%	wind-tunnel emissivity
				6.00%	combined bias uncertainty



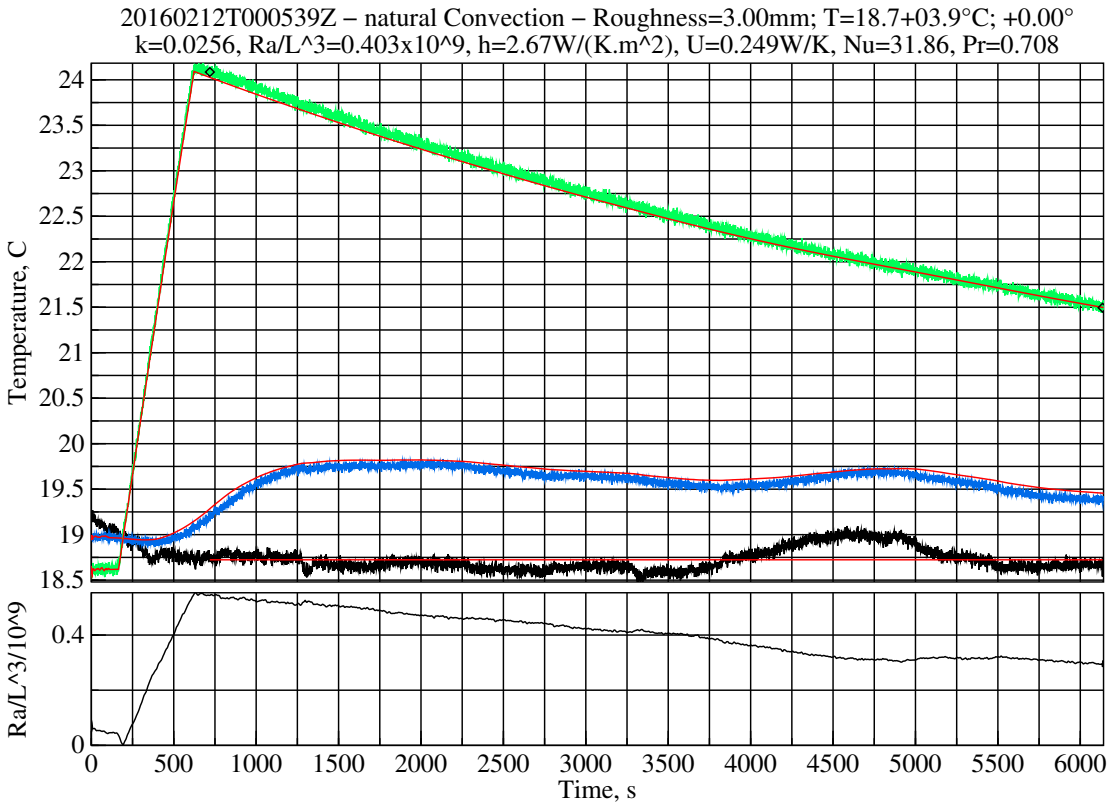
Estimated measurement uncertainties of natural convection at $\theta = -36.0$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	4.09K	+50.2%/K	0.10K	5.02%	LM35C differential
P	101kPa	+0.0006%/Pa	1.5kPa	0.84%	MPXH6115A6U air pressure
C_{pt}	4.69kJ/K	+0.038%/(J/K)	47J/K	1.77%	plate thermal capacity
C_S	1.000	−20.4%	0.050	1.02%	side reuptake
C_B	1.000	−5.70%	0.100	0.57%	back reuptake
L_c	0.305m	+519%/m	500um	0.26%	characteristic length
D_{PIR}	25.4mm	−320%/m	1.0mm	0.32%	insulation thickness
L_m	3.57mm	+1106%/m	500um	0.55%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.309\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	0.34%	PIR thermal conductivity
ϵ_{XPS}	0.515	+35.0%	0.010	0.35%	XPS emissivity
ϵ_{tp}	0.890	+42.1%	0.015	0.63%	tape emissivity
Ω_{tp}	0.540	+28.5%	0.020	0.57%	tape coverage
ϵ_{rs}	0.040	+148%	0.010	1.48%	test-surface emissivity
ϵ_{wt}	0.900	+69.0%	0.025	1.73%	wind-tunnel emissivity
				6.09%	combined bias uncertainty



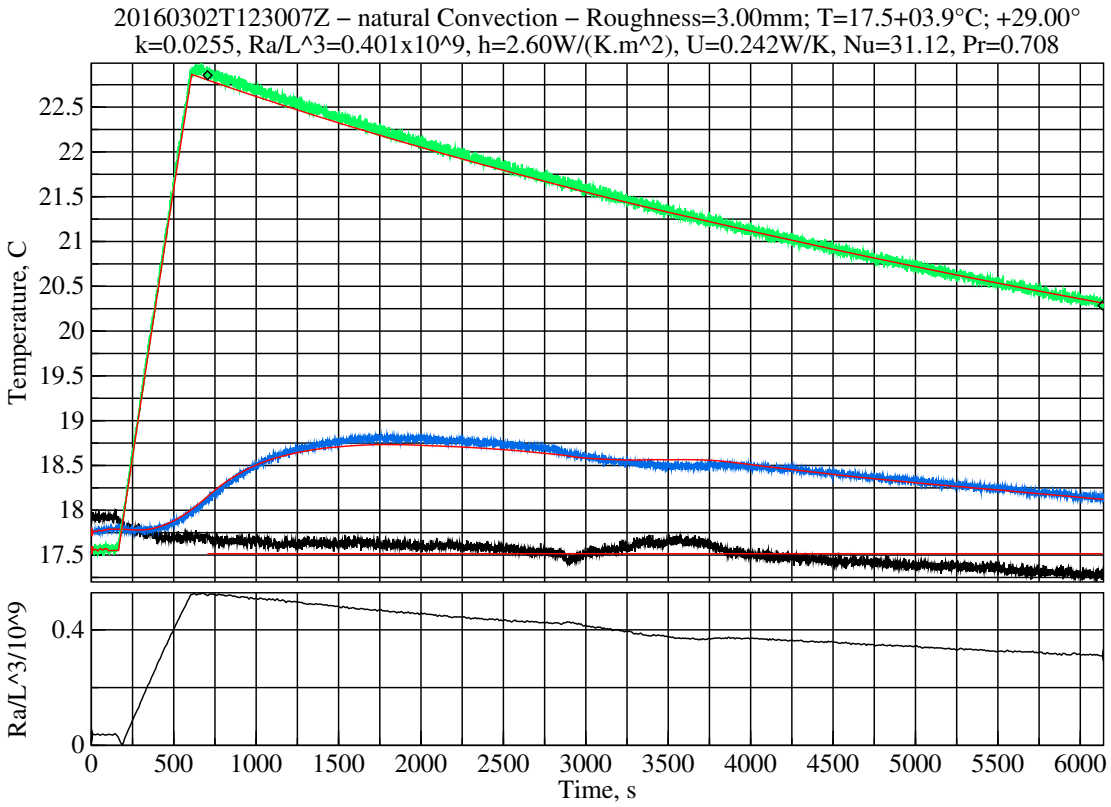
Estimated measurement uncertainties of natural convection at $\theta = -14.0$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	3.90K	+64.8%/K	0.10K	6.48%	LM35C differential
T_{bb}	291K	+0.412%/K	0.50K	0.21%	radiative temperature
P	99.3kPa	+0.0007%/Pa	1.5kPa	1.02%	MPXH6115A6U air pressure
C_{pt}	4.69kJ/K	+0.047%/(J/K)	47J/K	2.19%	plate thermal capacity
C_S	1.000	−4.98%	0.050	0.25%	side reuptake
C_V	1.000	−15.1%	0.100	1.51%	vertical reuptake
L_c	0.305m	+663%/m	500um	0.33%	characteristic length
D_{PIR}	25.4mm	−594%/m	1.0mm	0.59%	insulation thickness
D_g	1.00mm	−602%/m	500um	0.30%	air gap
L_m	3.57mm	+1395%/m	500um	0.70%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.574\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	0.64%	PIR thermal conductivity
ϵ_{XPS}	0.515	+45.5%	0.010	0.45%	XPS emissivity
ϵ_{tp}	0.890	+54.5%	0.015	0.82%	tape emissivity
Ω_{tp}	0.540	+37.1%	0.020	0.74%	tape coverage
ϵ_{rs}	0.040	+189%	0.010	1.89%	test-surface emissivity
ϵ_{wt}	0.900	+89.7%	0.025	2.24%	wind-tunnel emissivity
θ	-14.0°	+0.465%/°	0.50°	0.23%	plate angle
				7.86%	combined bias uncertainty



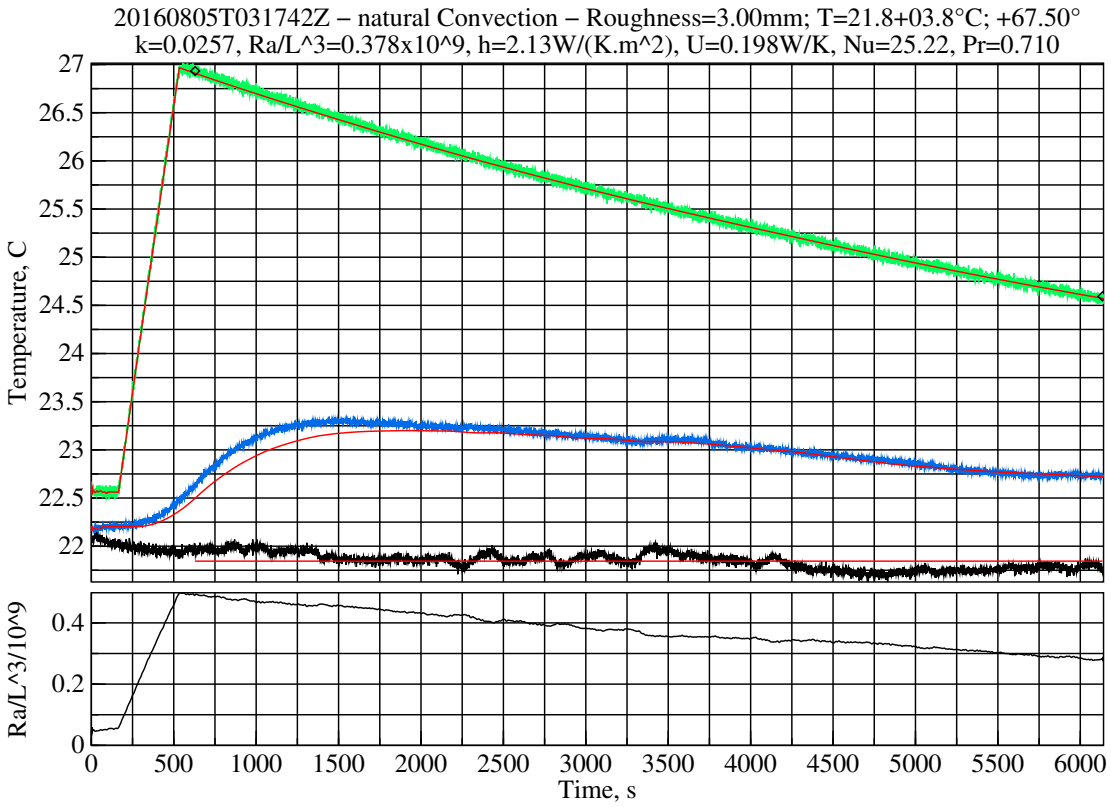
Estimated measurement uncertainties of natural convection at $\theta = 0.0$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	3.91K	+65.2%/K	0.10K	6.52%	LM35C differential
T_{bb}	292K	+0.416%/K	0.50K	0.21%	radiative temperature
P	100kPa	+0.0007%/Pa	1.5kPa	1.02%	MPXH6115A6U air pressure
C_{pt}	4.69kJ/K	+0.047%/(J/K)	47J/K	2.21%	plate thermal capacity
C_V	1.000	−15.5%	0.100	1.55%	vertical reuptake
L_c	0.305m	+664%/m	500um	0.33%	characteristic length
D_{PIR}	25.4mm	−625%/m	1.0mm	0.63%	insulation thickness
D_g	1.00mm	−634%/m	500um	0.32%	air gap
L_m	3.57mm	+1382%/m	500um	0.69%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.605\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	0.67%	PIR thermal conductivity
ϵ_{XPS}	0.515	+46.2%	0.010	0.46%	XPS emissivity
ϵ_{tp}	0.890	+55.3%	0.015	0.83%	tape emissivity
Ω_{tp}	0.540	+37.7%	0.020	0.75%	tape coverage
ϵ_{rs}	0.040	+189%	0.010	1.89%	test-surface emissivity
ϵ_{wt}	0.900	+91.0%	0.025	2.27%	wind-tunnel emissivity
				7.92%	combined bias uncertainty



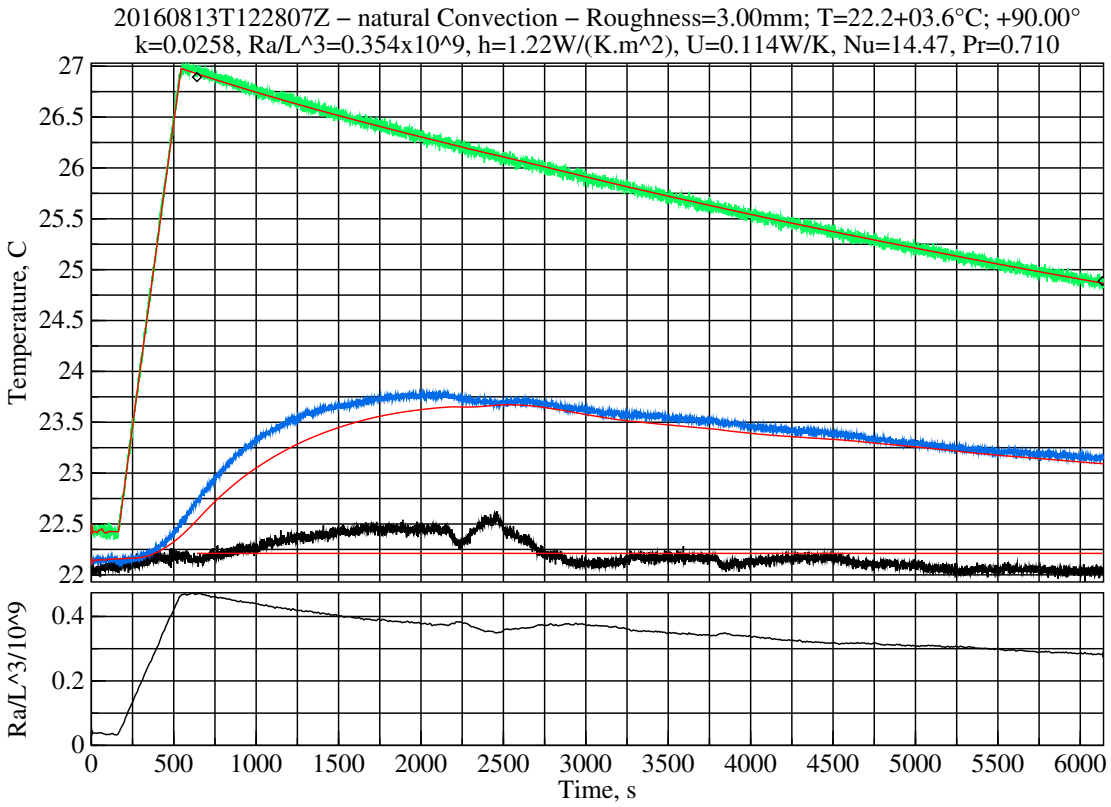
Estimated measurement uncertainties of natural convection at $\theta = 29.0$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	3.94K	+65.9%/K	0.10K	6.59%	LM35C differential
T_{bb}	291K	+0.422%/K	0.50K	0.21%	radiative temperature
P	98.8kPa	+0.0007%/Pa	1.5kPa	1.04%	MPXH6115A6U air pressure
C_{pt}	4.69kJ/K	+0.048%/(J/K)	47J/K	2.25%	plate thermal capacity
C_V	1.000	−5.75%	0.100	0.57%	vertical reuptake
L_c	0.305m	+678%/m	500um	0.34%	characteristic length
D_{PIR}	25.4mm	−652%/m	1.0mm	0.65%	insulation thickness
D_g	1.00mm	−661%/m	500um	0.33%	air gap
L_m	3.57mm	+1450%/m	500um	0.73%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.631\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	0.70%	PIR thermal conductivity
ϵ_{XPS}	0.515	+46.4%	0.010	0.46%	XPS emissivity
ϵ_{tp}	0.890	+55.8%	0.015	0.84%	tape emissivity
Ω_{tp}	0.540	+37.9%	0.020	0.76%	tape coverage
ϵ_{rs}	0.040	+195%	0.010	1.95%	test-surface emissivity
ϵ_{wt}	0.900	+91.9%	0.025	2.30%	wind-tunnel emissivity
θ	29.0°	−0.412%/°	0.50°	0.21%	plate angle
				7.89%	combined bias uncertainty



Estimated measurement uncertainties of natural convection at $\theta = 67.5$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	3.78K	+82.6%/K	0.10K	8.26%	LM35C differential
T_{bb}	295K	+0.557%/K	0.50K	0.28%	radiative temperature
P	101kPa	+0.0007%/Pa	1.5kPa	1.11%	MPXH6115A6U air pressure
C_{pt}	4.69kJ/K	+0.058%/(J/K)	47J/K	2.74%	plate thermal capacity
C_V	1.000	−3.63%	0.100	0.36%	vertical reuptake
L_c	0.305m	+836%/m	500um	0.42%	characteristic length
D_{PIR}	25.4mm	−696%/m	1.0mm	0.70%	insulation thickness
D_g	1.00mm	−706%/m	500um	0.35%	air gap
L_m	3.57mm	+1927%/m	500um	0.96%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.673\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	0.75%	PIR thermal conductivity
ϵ_{XPS}	0.515	+61.2%	0.010	0.61%	XPS emissivity
ϵ_{tp}	0.890	+73.6%	0.015	1.10%	tape emissivity
Ω_{tp}	0.540	+49.9%	0.020	1.00%	tape coverage
ϵ_{rs}	0.040	+258%	0.010	2.58%	test-surface emissivity
ϵ_b	0.190	+17.5%	0.020	0.35%	back emissivity
ϵ_{wt}	0.900	+123%	0.025	3.08%	wind-tunnel emissivity
θ	67.5°	−0.521%/°	0.50°	0.26%	plate angle
				9.92%	combined bias uncertainty



Estimated measurement uncertainties of natural convection at $\theta = 90.0$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
T	297K	+0.827%/K	0.50K	0.41%	LM35C temperature sensor
ΔT	3.59K	+123%/K	0.10K	12.27%	LM35C differential
T_{bb}	295K	+0.889%/K	0.50K	0.44%	radiative temperature
P	101kPa	+0.0008%/Pa	1.5kPa	1.19%	MPXH6115A6U air pressure
C_{pt}	4.69kJ/K	+0.085%/(J/K)	47J/K	4.01%	plate thermal capacity
L_c	0.305m	+1225%/m	500um	0.61%	characteristic length
L_w	0.305m	+419%/m	500um	0.21%	plate width
D_{PIR}	25.4mm	−1006%/m	1.0mm	1.01%	insulation thickness
D_g	1.00mm	−1020%/m	500um	0.51%	air gap
L_m	3.57mm	+3040%/m	500um	1.52%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.973\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	1.08%	PIR thermal conductivity
ϵ_{XPS}	0.515	+97.1%	0.010	0.97%	XPS emissivity
ϵ_{tp}	0.890	+117%	0.015	1.75%	tape emissivity
Ω_{tp}	0.540	+79.1%	0.020	1.58%	tape coverage
ϵ_{rs}	0.040	+408%	0.010	4.08%	test-surface emissivity
ϵ_b	0.190	+35.6%	0.020	0.71%	back emissivity
ϵ_{wt}	0.900	+197%	0.025	4.91%	wind-tunnel emissivity
θ	90.0°	−1.03%/°	0.50°	0.51%	plate angle
				14.89%	combined bias uncertainty