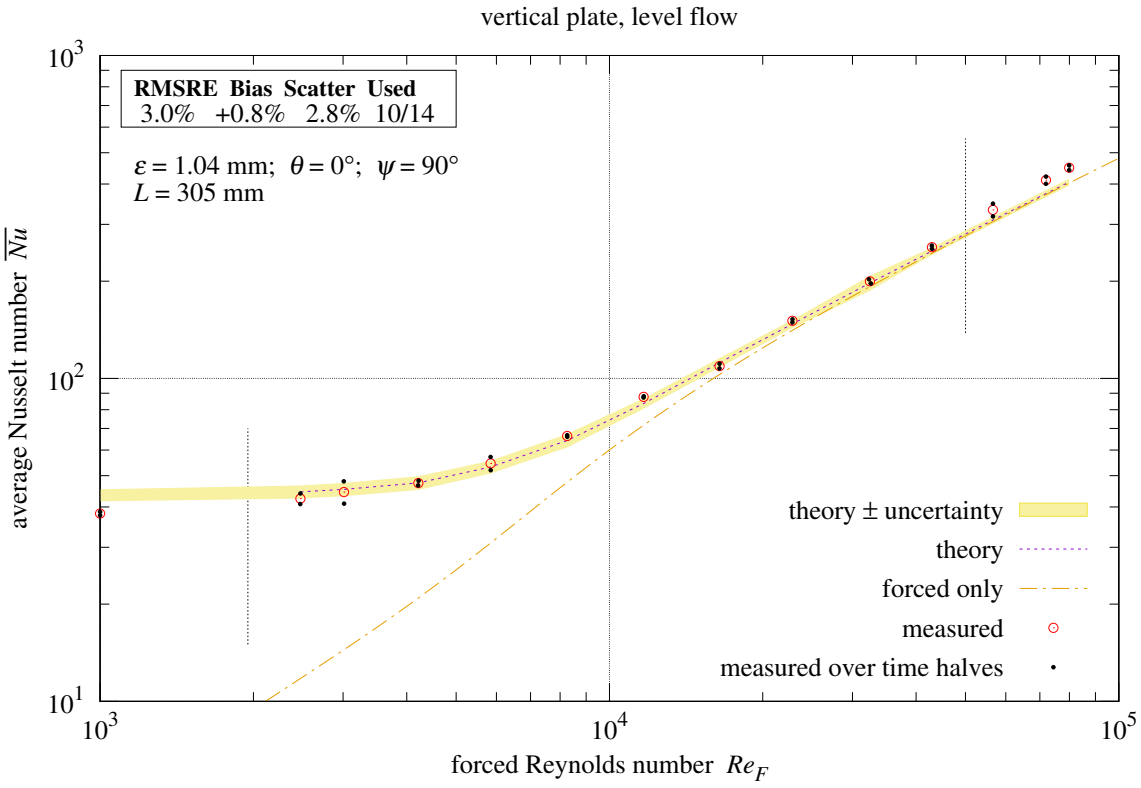
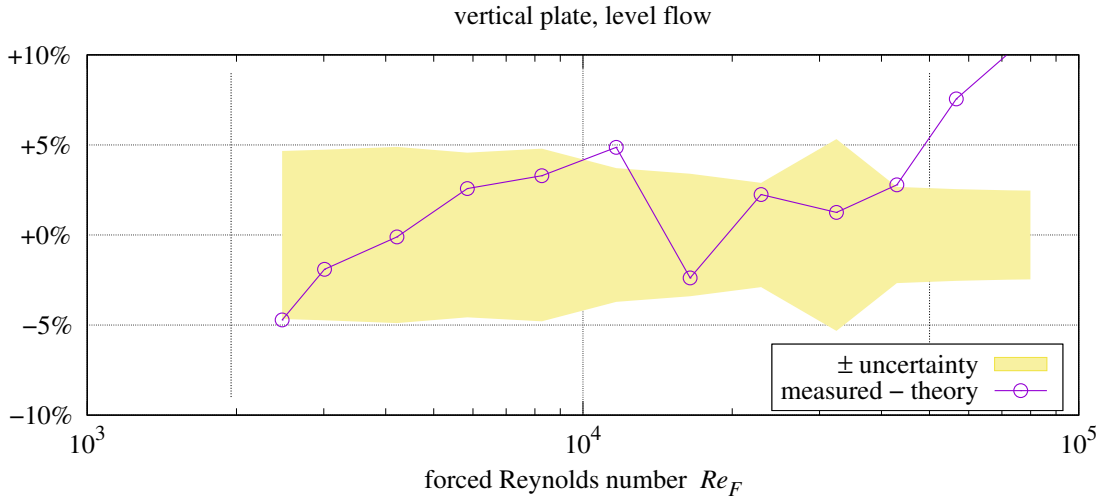
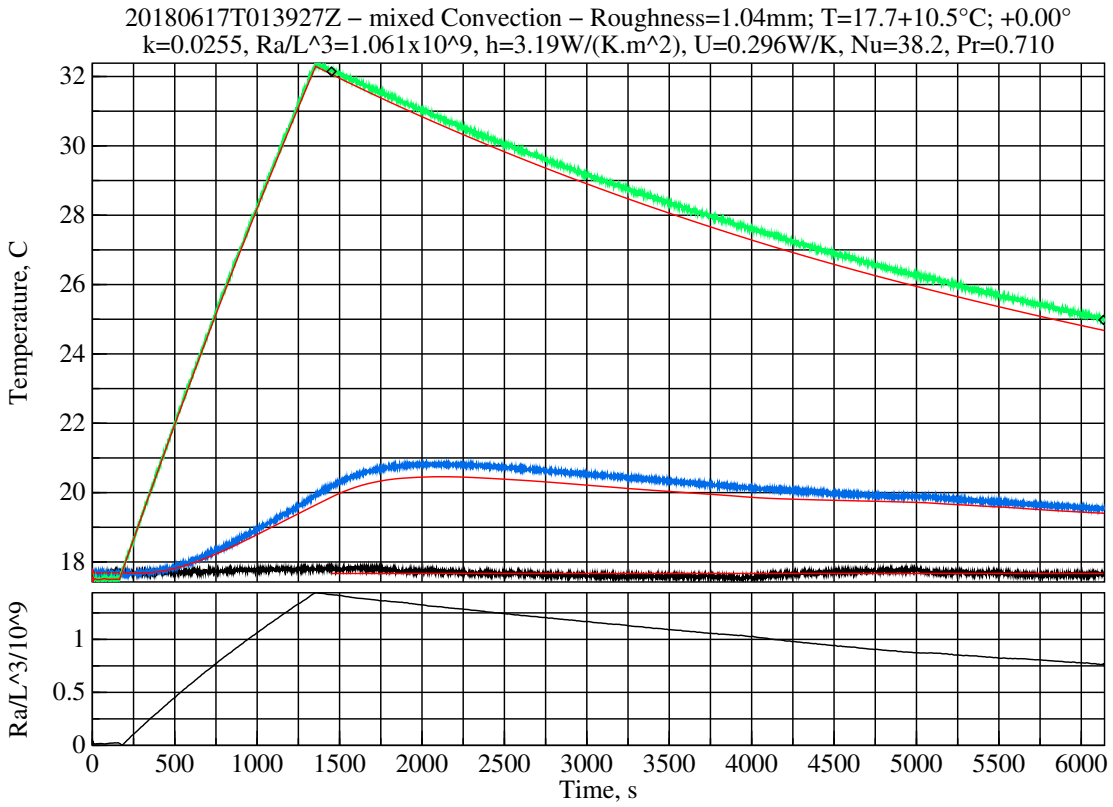
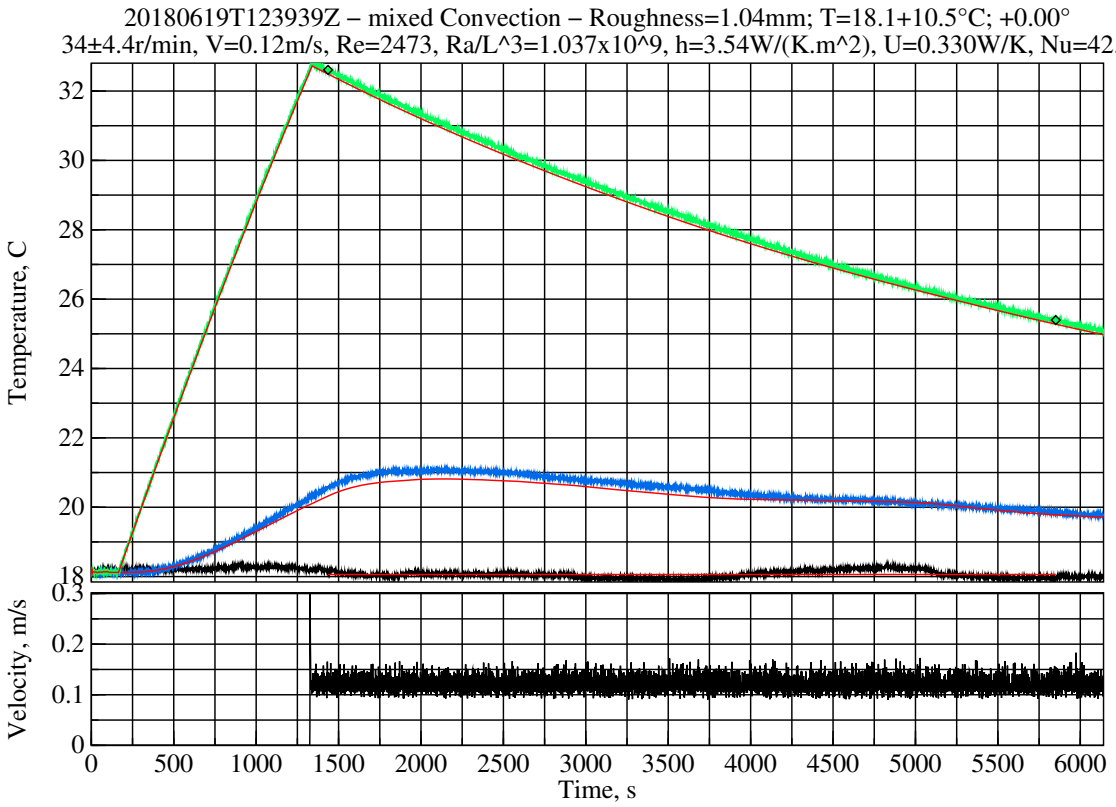

vertical plate, level flow
RMSRE Bias Scatter Used
3.0% +0.8% 2.8% 10/14
ε = 1.04 mm; θ = 0°; ψ = 90°
L = 305 mm
theory ± uncertainty
theory
forced only
measured
measured over time halves
average Nusselt number Nu
forced Reynolds number Re_F
10^3
10^2
10^1
10^4
10^5


vertical plate, level flow
+10%
+5%
+0%
−5%
−10%
± uncertainty
measured − theory
forced Reynolds number Re_F
10^3
10^4
10^5



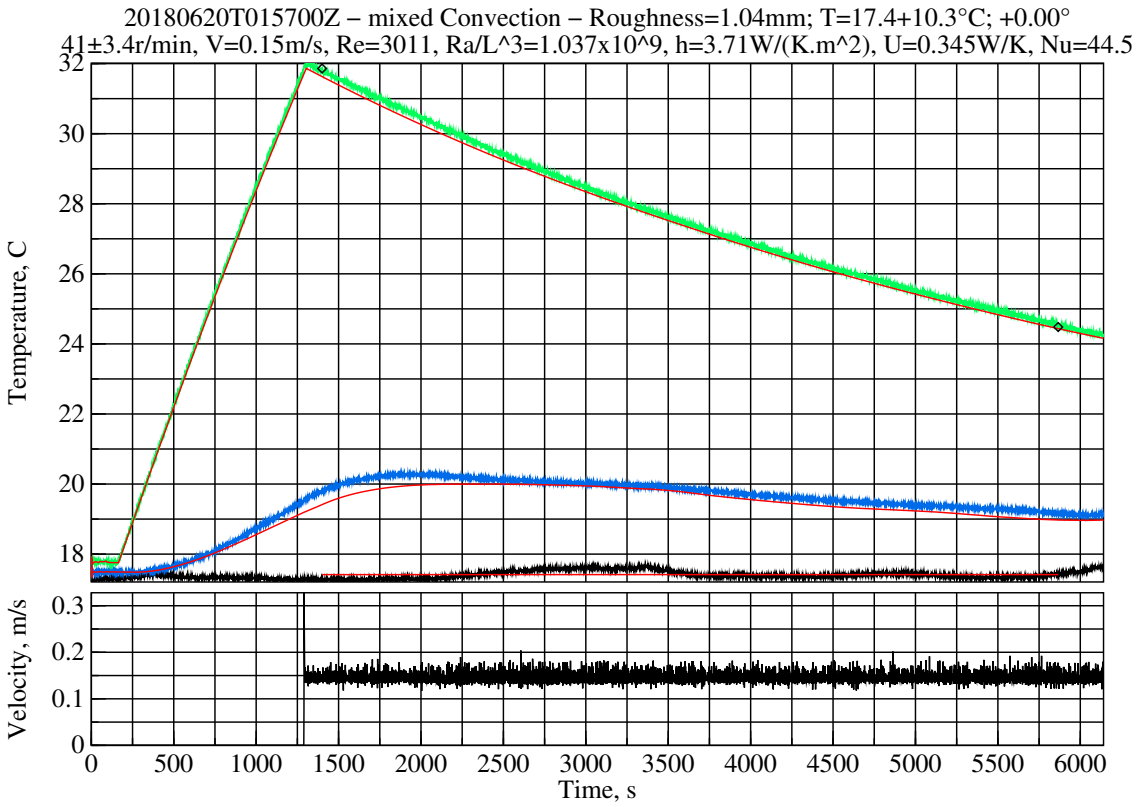
Estimated measurement uncertainties of natural convection at $\theta = 0.0$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	10.5K	+22.0%/K	0.10K	2.20%	LM35C differential
P	101kPa	+0.0007%/Pa	1.5kPa	1.02%	MPXH6115A6U air pressure
C_{pt}	4.24kJ/K	+0.046%/(J/K)	42J/K	1.96%	plate thermal capacity
C_V	1.000	−13.2%	0.100	1.32%	vertical reuptake
L_c	0.305m	+594%/m	500um	0.30%	characteristic length
D_{PIR}	25.4mm	−514%/m	1.0mm	0.51%	insulation thickness
D_g	1.00mm	−521%/m	500um	0.26%	air gap
L_m	3.57mm	+1084%/m	500um	0.54%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.497\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	0.55%	PIR thermal conductivity
ϵ_{XPS}	0.515	+35.4%	0.010	0.35%	XPS emissivity
ϵ_{tp}	0.890	+42.5%	0.015	0.64%	tape emissivity
Ω_{tp}	0.540	+28.9%	0.020	0.58%	tape coverage
ϵ_{rs}	0.040	+147%	0.010	1.47%	test-surface emissivity
ϵ_{wt}	0.900	+69.5%	0.025	1.74%	wind-tunnel emissivity
				4.32%	combined bias uncertainty



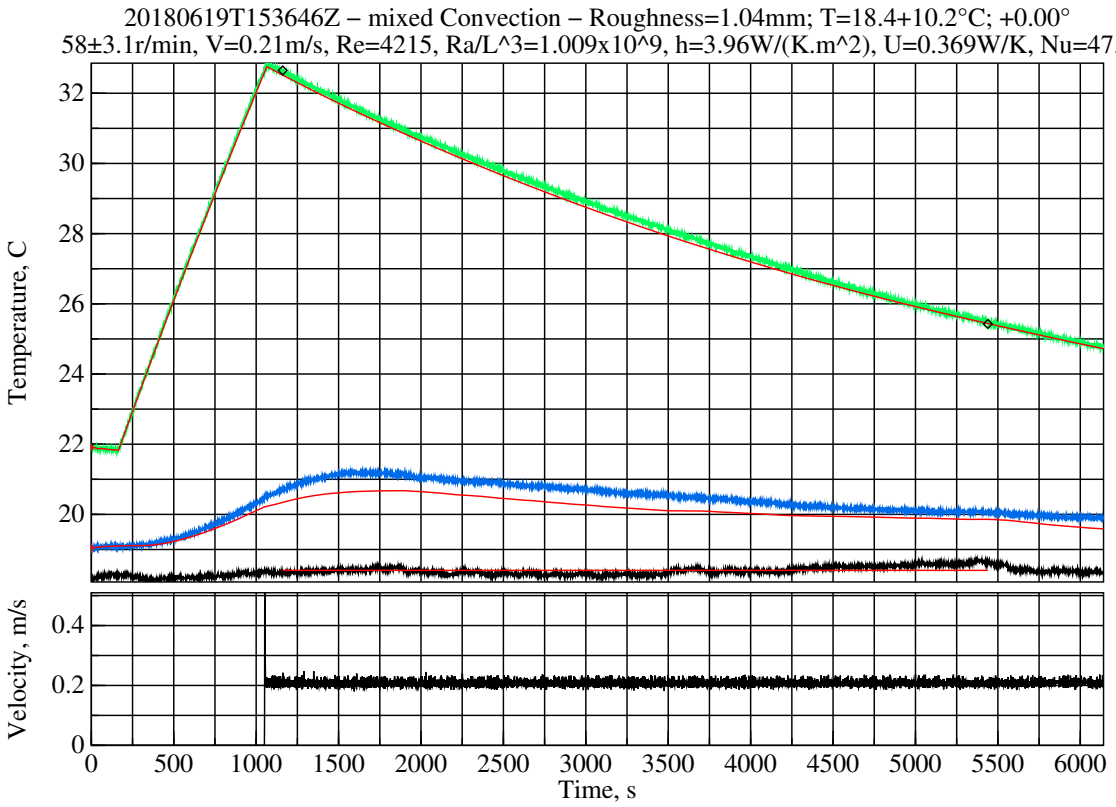
Estimated measurement uncertainties, bi-level 1mm roughness at $Re = 2473$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	10.5K	+21.6%/K	0.10K	2.16%	LM35C differential
P	99.8kPa	+0.0007%/Pa	1.5kPa	1.07%	MPXH6115A6U air pressure
C_{pt}	4.24kJ/K	+0.046%/(J/K)	42J/K	1.93%	plate thermal capacity
C_V	1.000	−12.8%	0.100	1.28%	vertical reuptake
L_c	0.305m	+579%/m	500um	0.29%	characteristic length
D_{PIR}	25.4mm	−498%/m	1.0mm	0.50%	insulation thickness
D_g	1.00mm	−505%/m	500um	0.25%	air gap
L_m	3.57mm	+1085%/m	500um	0.54%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.485\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	0.54%	PIR thermal conductivity
ϵ_{XPS}	0.515	+34.5%	0.010	0.35%	XPS emissivity
ϵ_{tp}	0.890	+41.4%	0.015	0.62%	tape emissivity
Ω_{tp}	0.540	+28.1%	0.020	0.56%	tape coverage
ϵ_{rs}	0.040	+143%	0.010	1.43%	test-surface emissivity
ϵ_{wt}	0.900	+67.7%	0.025	1.69%	wind-tunnel emissivity
				4.24%	combined bias uncertainty
Symbol	**Nominal**	**Sensitivity**	**Variability**	**Uncertainty**	**Component**
ω	34.2r/min	+0.218%/(r/min)	4.4r/min	0.96%	fan rotation rate
				4.66%	RSS combined uncertainty



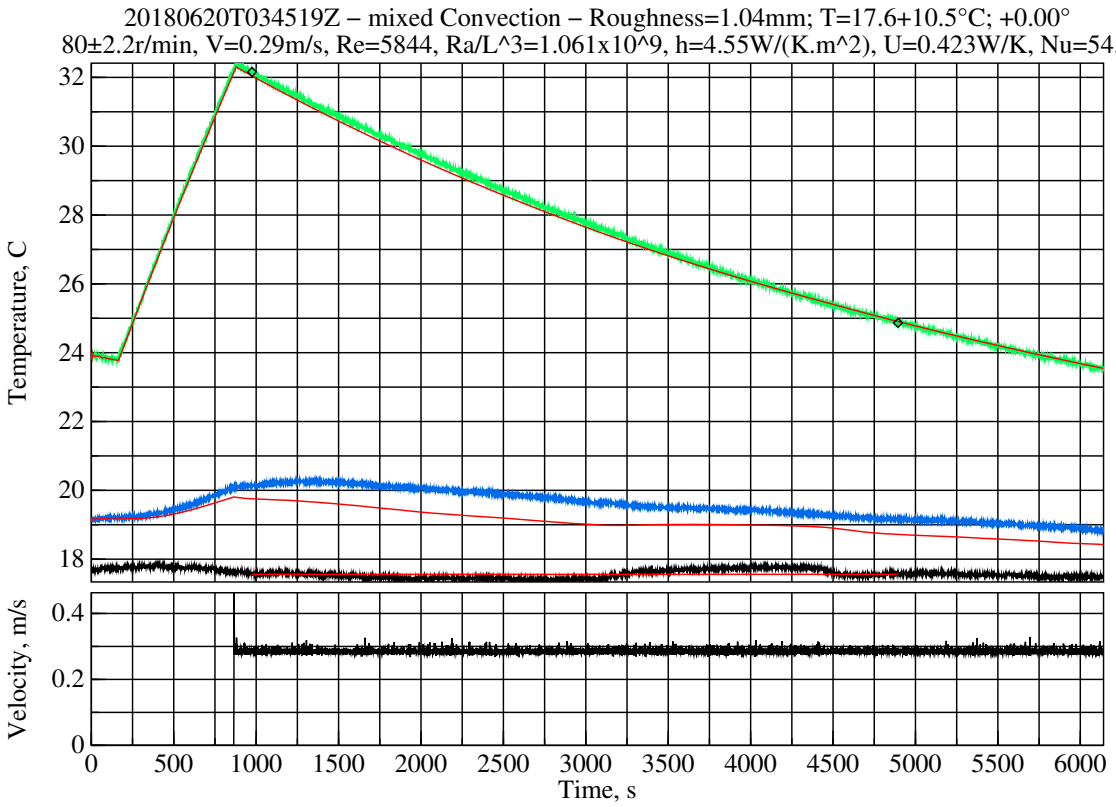
Estimated measurement uncertainties, bi-level 1mm roughness at $Re = 3011$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	10.3K	+21.7%/K	0.10K	2.17%	LM35C differential
P	100kPa	+0.0007%/Pa	1.5kPa	1.10%	MPXH6115A6U air pressure
C_{pt}	4.24kJ/K	+0.045%/(J/K)	42J/K	1.92%	plate thermal capacity
C_V	1.000	−12.5%	0.100	1.25%	vertical reuptake
L_c	0.305m	+571%/m	500um	0.29%	characteristic length
D_{PIR}	25.4mm	−481%/m	1.0mm	0.48%	insulation thickness
D_g	1.00mm	−488%/m	500um	0.24%	air gap
L_m	3.57mm	+1069%/m	500um	0.53%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.469\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	0.52%	PIR thermal conductivity
ϵ_{XPS}	0.515	+33.6%	0.010	0.34%	XPS emissivity
ϵ_{tp}	0.890	+40.3%	0.015	0.60%	tape emissivity
Ω_{tp}	0.540	+27.4%	0.020	0.55%	tape coverage
ϵ_{rs}	0.040	+140%	0.010	1.40%	test-surface emissivity
ϵ_{wt}	0.900	+66.1%	0.025	1.65%	wind-tunnel emissivity
				4.20%	combined bias uncertainty
Symbol	**Nominal**	**Sensitivity**	**Variability**	**Uncertainty**	**Component**
ω	41.3r/min	+0.318%/(r/min)	3.4r/min	1.09%	fan rotation rate
				4.74%	RSS combined uncertainty



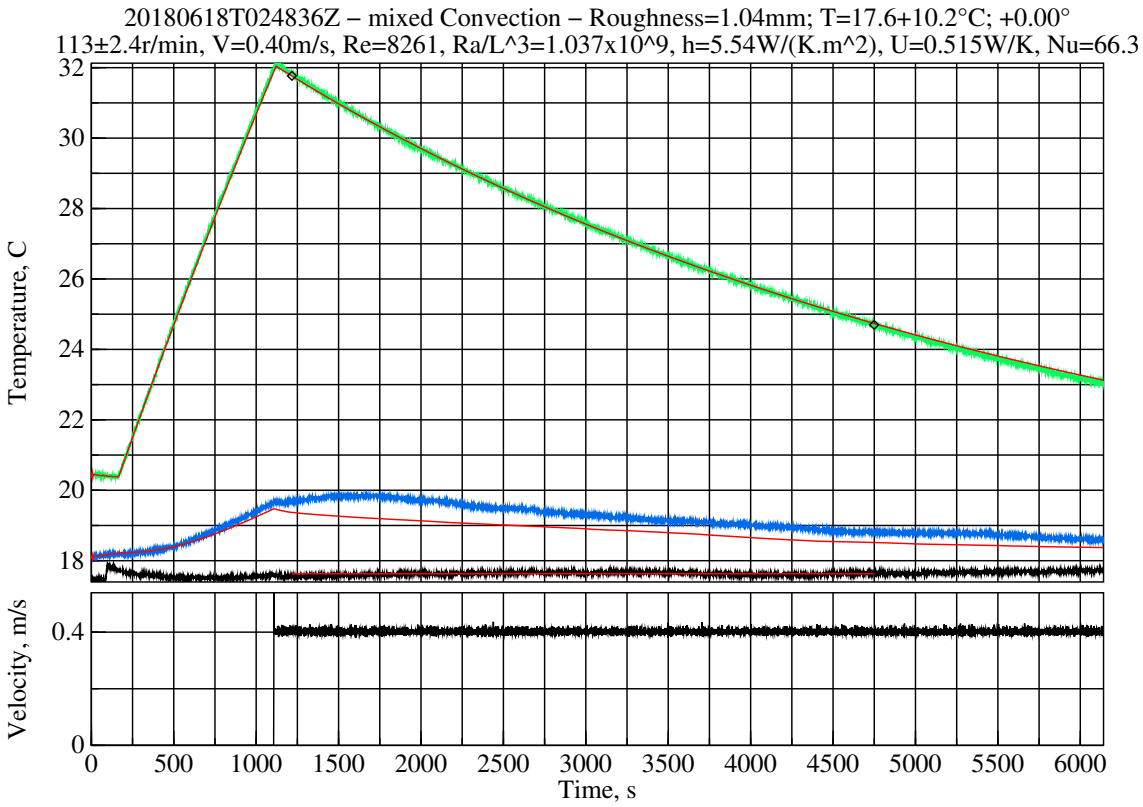
Estimated measurement uncertainties, bi-level 1mm roughness at $Re = 4215$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	10.2K	+21.2%/K	0.10K	2.12%	LM35C differential
P	99.9kPa	+0.0008%/Pa	1.5kPa	1.19%	MPXH6115A6U air pressure
C_{pt}	4.24kJ/K	+0.044%/(J/K)	42J/K	1.89%	plate thermal capacity
η	0.402	+60.6%	0.004	0.24%	anemometer calibration
C_V	1.000	−11.9%	0.100	1.19%	vertical reuptake
L_c	0.305m	+565%/m	500um	0.28%	characteristic length
D_{PIR}	25.4mm	−498%/m	1.0mm	0.50%	insulation thickness
D_g	1.00mm	−506%/m	500um	0.25%	air gap
L_m	3.57mm	+1048%/m	500um	0.52%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.487\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	0.54%	PIR thermal conductivity
ϵ_{XPS}	0.515	+32.4%	0.010	0.32%	XPS emissivity
ϵ_{tp}	0.890	+38.8%	0.015	0.58%	tape emissivity
Ω_{tp}	0.540	+26.4%	0.020	0.53%	tape coverage
ϵ_{rs}	0.040	+134%	0.010	1.34%	test-surface emissivity
ϵ_{wt}	0.900	+63.3%	0.025	1.58%	wind-tunnel emissivity
				4.13%	combined bias uncertainty
Symbol	**Nominal**	**Sensitivity**	**Variability**	**Uncertainty**	**Component**
ω	58.4r/min	+0.417%/(r/min)	3.1r/min	1.31%	fan rotation rate
				4.89%	RSS combined uncertainty



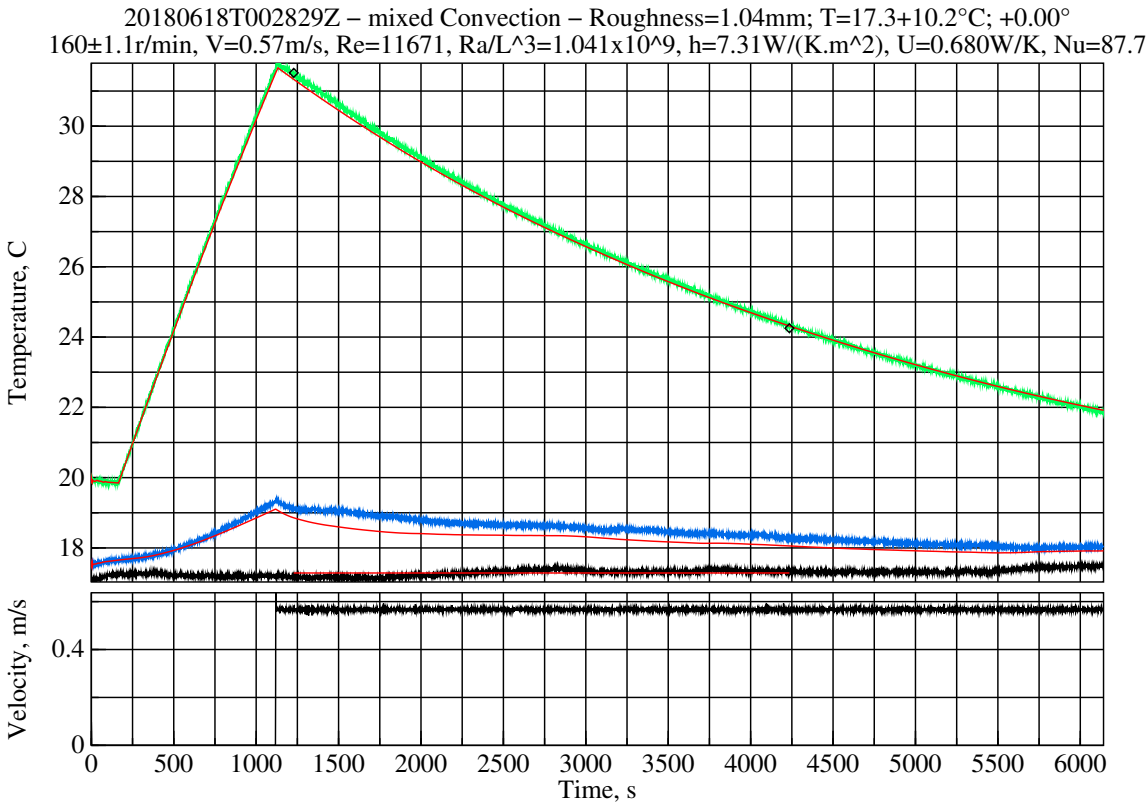
Estimated measurement uncertainties, bi-level 1mm roughness at $Re = 5844$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	10.5K	+19.3%/K	0.10K	1.93%	LM35C differential
P	100kPa	+0.0009%/Pa	1.5kPa	1.34%	MPXH6115A6U air pressure
C_{pt}	4.24kJ/K	+0.042%/(J/K)	42J/K	1.80%	plate thermal capacity
η	0.402	+109%	0.004	0.44%	anemometer calibration
C_V	1.000	−10.7%	0.100	1.07%	vertical reuptake
L_c	0.305m	+562%/m	500um	0.28%	characteristic length
ς	2.00mm	−4474%/m	100um	0.45%	post height
D_{PIR}	25.4mm	−477%/m	1.0mm	0.48%	insulation thickness
D_g	1.00mm	−484%/m	500um	0.24%	air gap
L_m	3.57mm	+961%/m	500um	0.48%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.467\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	0.52%	PIR thermal conductivity
ϵ_{XPS}	0.515	+28.7%	0.010	0.29%	XPS emissivity
ϵ_{tp}	0.890	+34.5%	0.015	0.52%	tape emissivity
Ω_{tp}	0.540	+23.4%	0.020	0.47%	tape coverage
ϵ_{rs}	0.040	+119%	0.010	1.19%	test-surface emissivity
ϵ_{wt}	0.900	+56.1%	0.025	1.40%	wind-tunnel emissivity
				3.91%	combined bias uncertainty
Symbol	**Nominal**	**Sensitivity**	**Variability**	**Uncertainty**	**Component**
ω	80.3r/min	+0.547%/(r/min)	2.2r/min	1.19%	fan rotation rate
				4.57%	RSS combined uncertainty



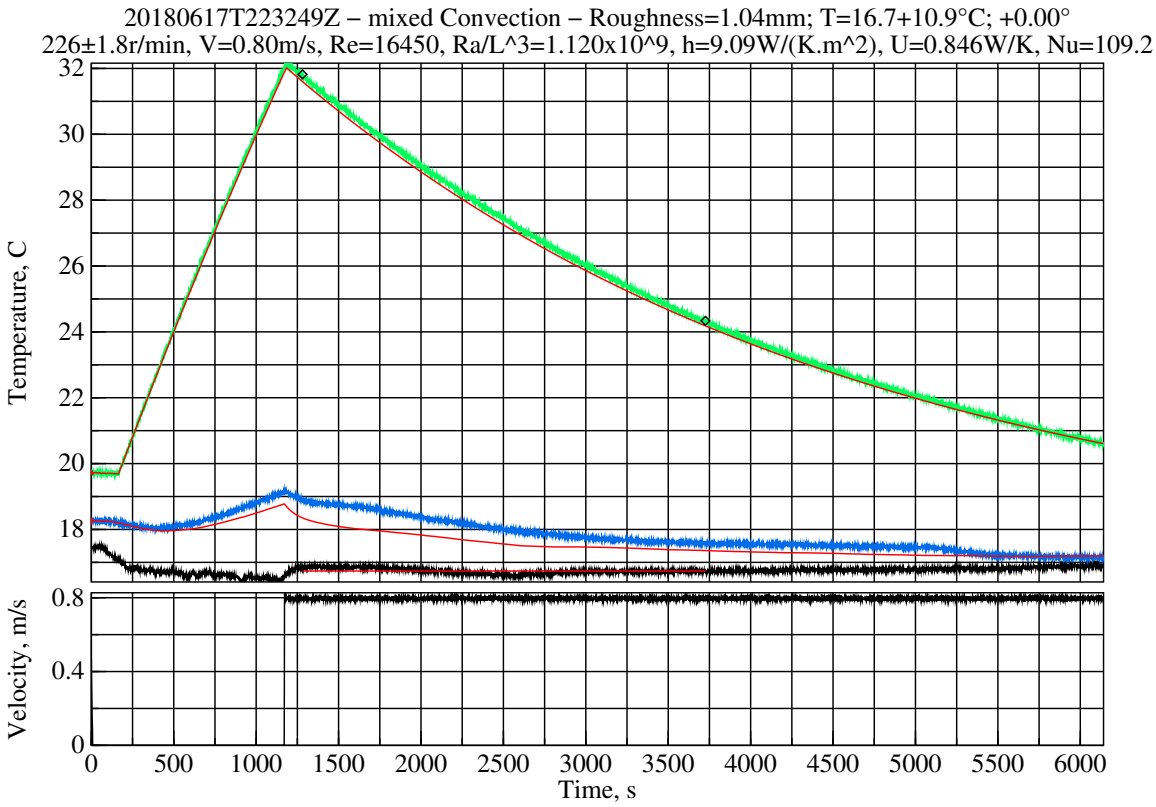
Estimated measurement uncertainties, bi-level 1mm roughness at $Re = 8261$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	10.2K	+18.1%/K	0.10K	1.81%	LM35C differential
P	101kPa	+0.0010%/Pa	1.5kPa	1.51%	MPXH6115A6U air pressure
C_{pt}	4.24kJ/K	+0.039%/(J/K)	42J/K	1.66%	plate thermal capacity
η	0.402	+173%	0.004	0.70%	anemometer calibration
C_V	1.000	−8.85%	0.100	0.89%	vertical reuptake
L_c	0.305m	+529%/m	500um	0.26%	characteristic length
L_T	8.34mm	+4399%/m	100um	0.44%	post length
ς	2.00mm	−11073%/m	100um	1.11%	post height
D_{PIR}	25.4mm	−419%/m	1.0mm	0.42%	insulation thickness
D_g	1.00mm	−425%/m	500um	0.21%	air gap
L_m	3.57mm	+832%/m	500um	0.42%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.412\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	0.46%	PIR thermal conductivity
ϵ_{XPS}	0.515	+23.7%	0.010	0.24%	XPS emissivity
ϵ_{tp}	0.890	+28.4%	0.015	0.43%	tape emissivity
Ω_{tp}	0.540	+19.3%	0.020	0.39%	tape coverage
ϵ_{rs}	0.040	+98.6%	0.010	0.99%	test-surface emissivity
ϵ_{wt}	0.900	+46.2%	0.025	1.15%	wind-tunnel emissivity
				3.80%	combined bias uncertainty
Symbol	**Nominal**	**Sensitivity**	**Variability**	**Uncertainty**	**Component**
ω	113r/min	+0.615%/(r/min)	2.4r/min	1.46%	fan rotation rate
				4.79%	RSS combined uncertainty



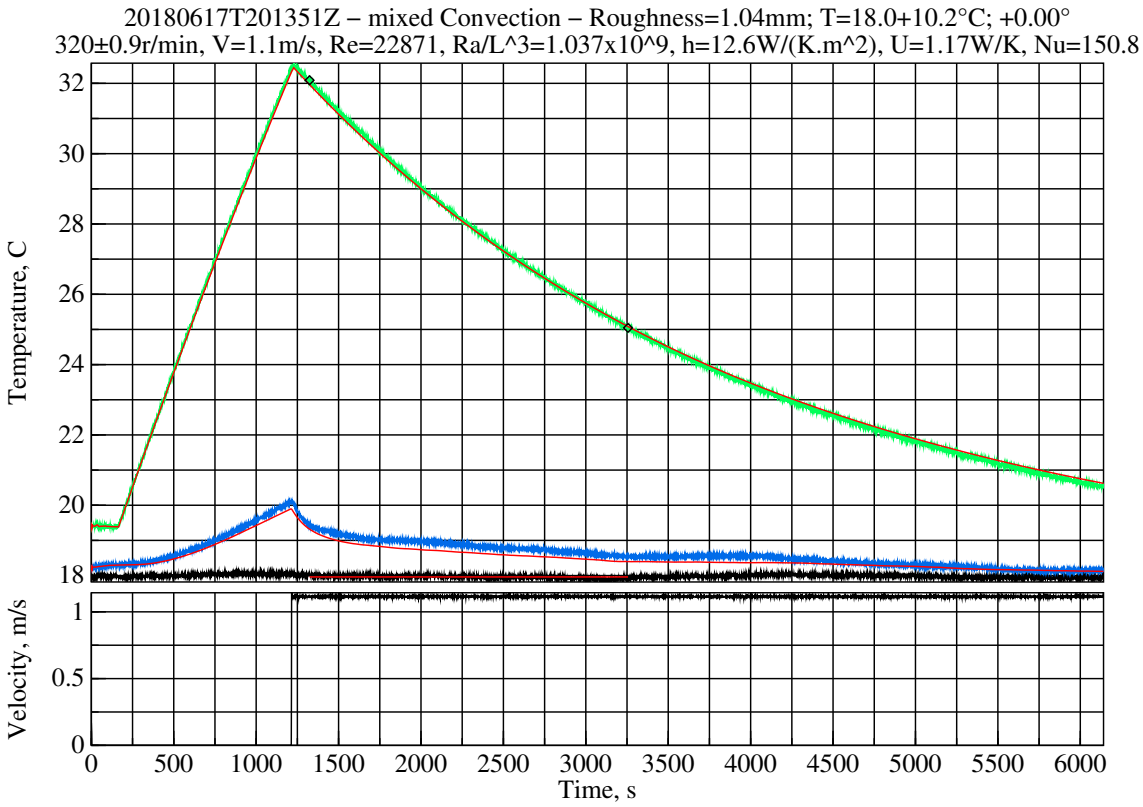
Estimated measurement uncertainties, bi-level 1mm roughness at $Re = 11672$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	10.2K	+16.0%/K	0.10K	1.60%	LM35C differential
P	101kPa	+0.0010%/Pa	1.5kPa	1.54%	MPXH6115A6U air pressure
C_{pt}	4.24kJ/K	+0.036%/(J/K)	42J/K	1.51%	plate thermal capacity
η	0.402	+210%	0.004	0.84%	anemometer calibration
C_V	1.000	−6.77%	0.100	0.68%	vertical reuptake
L_c	0.305m	+423%/m	500um	0.21%	characteristic length
L_T	8.34mm	+6683%/m	100um	0.67%	post length
ς	2.00mm	−12600%/m	100um	1.26%	post height
D_{PIR}	25.4mm	−337%/m	1.0mm	0.34%	insulation thickness
L_m	3.57mm	+682%/m	500um	0.34%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.333\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	0.37%	PIR thermal conductivity
ϵ_{tp}	0.890	+21.7%	0.015	0.32%	tape emissivity
Ω_{tp}	0.540	+14.7%	0.020	0.29%	tape coverage
ϵ_{rs}	0.040	+75.2%	0.010	0.75%	test-surface emissivity
ϵ_{wt}	0.900	+35.1%	0.025	0.88%	wind-tunnel emissivity
				3.53%	combined bias uncertainty
Symbol	**Nominal**	**Sensitivity**	**Variability**	**Uncertainty**	**Component**
ω	160r/min	+0.527%/(r/min)	1.1r/min	0.57%	fan rotation rate
				3.71%	RSS combined uncertainty



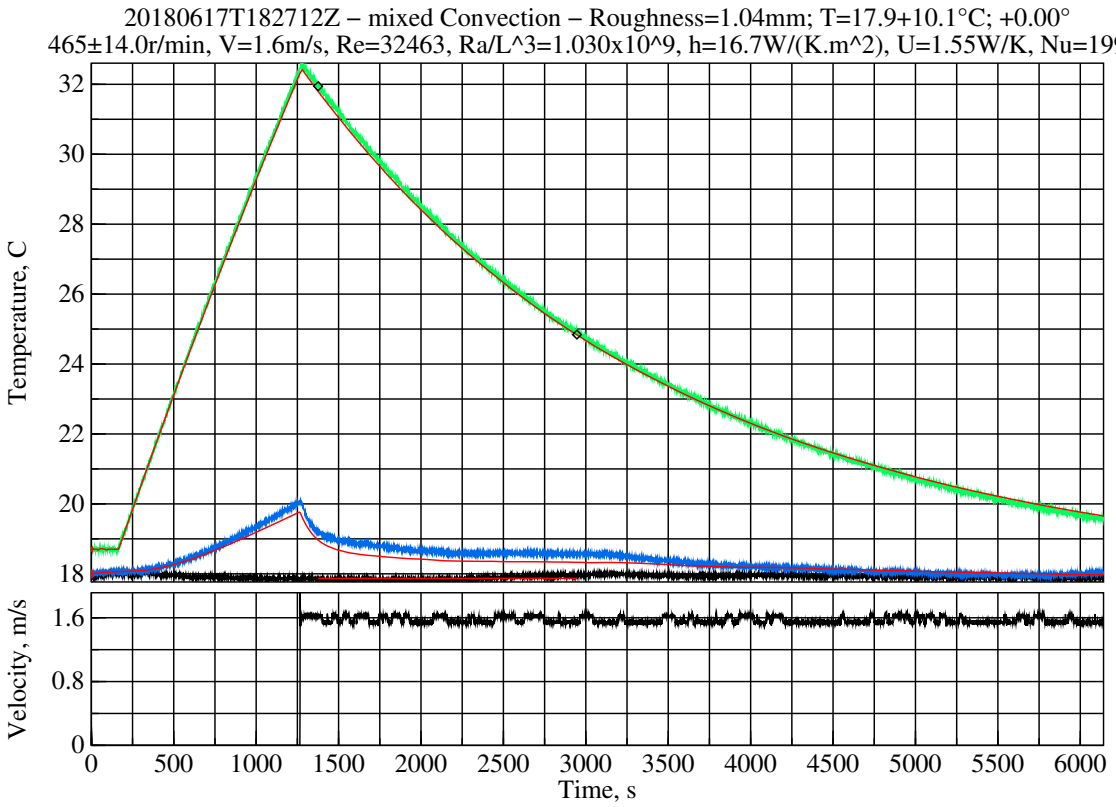
Estimated measurement uncertainties, bi-level 1mm roughness at $Re = 16448$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	10.9K	+13.3%/K	0.10K	1.33%	LM35C differential
P	101kPa	+0.0010%/Pa	1.5kPa	1.47%	MPXH6115A6U air pressure
C_{pt}	4.24kJ/K	+0.033%/(J/K)	42J/K	1.38%	plate thermal capacity
η	0.402	+215%	0.004	0.87%	anemometer calibration
C_V	1.000	−5.09%	0.100	0.51%	vertical reuptake
L_T	8.34mm	+8010%/m	100um	0.80%	post length
ς	2.00mm	−10203%/m	100um	1.02%	post height
D_{PIR}	25.4mm	−260%/m	1.0mm	0.26%	insulation thickness
L_m	3.57mm	+560%/m	500um	0.28%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.258\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	0.29%	PIR thermal conductivity
ϵ_{tp}	0.890	+16.0%	0.015	0.24%	tape emissivity
Ω_{tp}	0.540	+10.8%	0.020	0.22%	tape coverage
ϵ_{rs}	0.040	+55.6%	0.010	0.56%	test-surface emissivity
ϵ_{wt}	0.900	+25.9%	0.025	0.65%	wind-tunnel emissivity
				3.12%	combined bias uncertainty
Symbol	**Nominal**	**Sensitivity**	**Variability**	**Uncertainty**	**Component**
ω	226r/min	+0.383%/(r/min)	1.8r/min	0.68%	fan rotation rate
				3.40%	RSS combined uncertainty



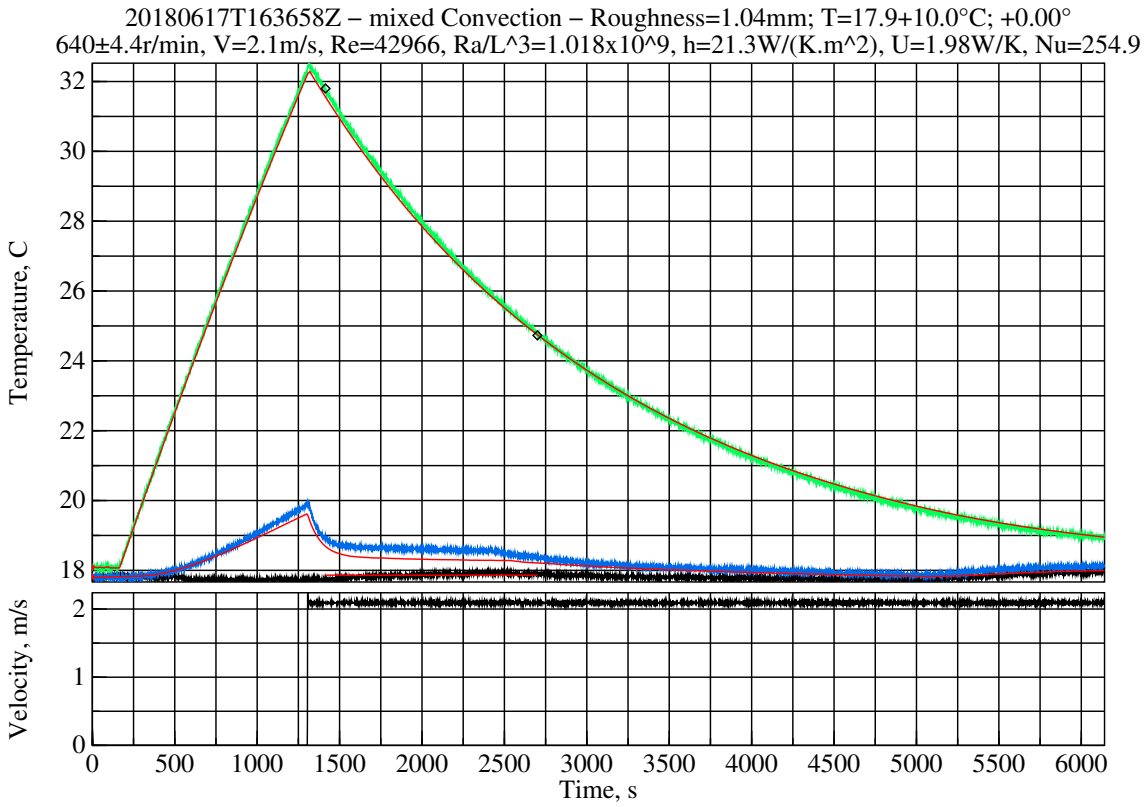
Estimated measurement uncertainties, bi-level 1mm roughness at $Re = 22870$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	10.2K	+13.1%/K	0.10K	1.31%	LM35C differential
P	101kPa	+0.0009%/Pa	1.5kPa	1.38%	MPXH6115A6U air pressure
C_{pt}	4.24kJ/K	+0.030%/(J/K)	42J/K	1.29%	plate thermal capacity
η	0.402	+208%	0.004	0.84%	anemometer calibration
C_V	1.000	−3.76%	0.100	0.38%	vertical reuptake
L_T	8.34mm	+8713%/m	100um	0.87%	post length
ς	2.00mm	−7344%/m	100um	0.73%	post height
D_{PIR}	25.4mm	−201%/m	1.0mm	0.20%	insulation thickness
L_m	3.57mm	+496%/m	500um	0.25%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.201\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	0.22%	PIR thermal conductivity
ϵ_{rs}	0.040	+42.0%	0.010	0.42%	test-surface emissivity
ϵ_{wt}	0.900	+19.6%	0.025	0.49%	wind-tunnel emissivity
				2.85%	combined bias uncertainty
Symbol	**Nominal**	**Sensitivity**	**Variability**	**Uncertainty**	**Component**
ω	320r/min	+0.261%/(r/min)	0.92r/min	0.24%	fan rotation rate
				2.89%	RSS combined uncertainty



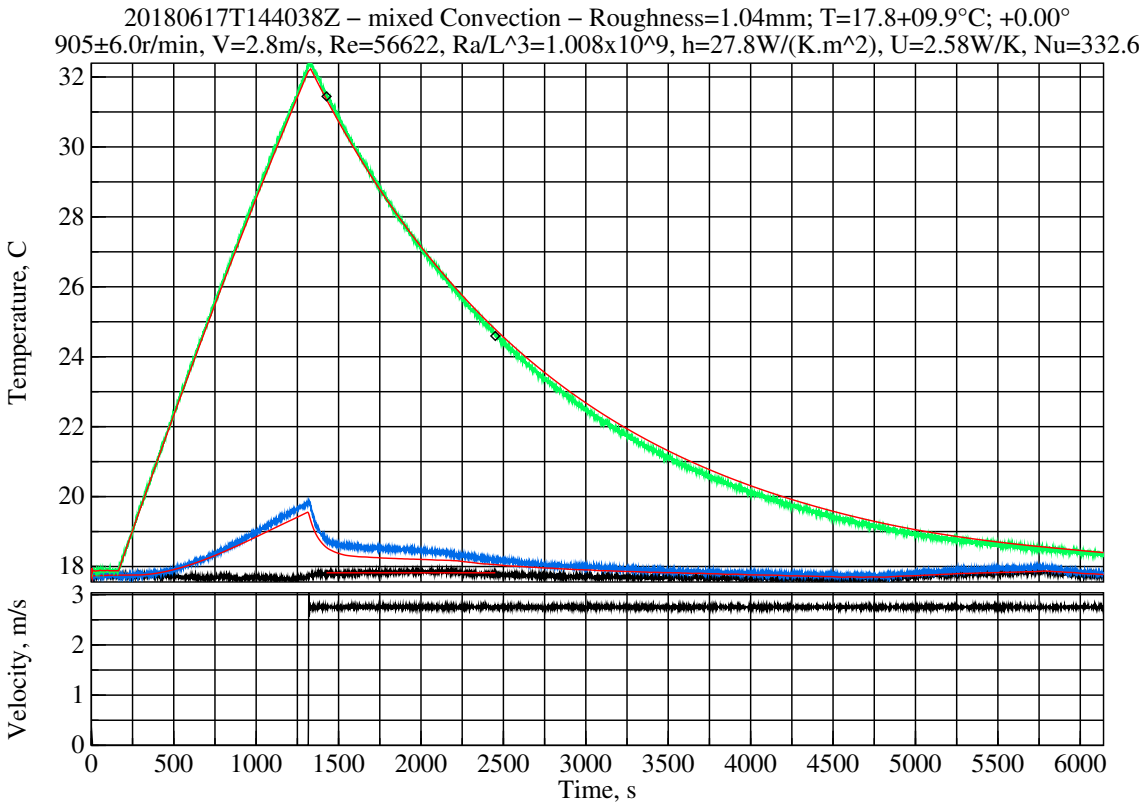
Estimated measurement uncertainties, bi-level 1mm roughness at $Re = 32461$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	10.1K	+12.3%/K	0.10K	1.23%	LM35C differential
P	101kPa	+0.0009%/Pa	1.5kPa	1.31%	MPXH6115A6U air pressure
C_{pt}	4.24kJ/K	+0.029%/(J/K)	42J/K	1.22%	plate thermal capacity
η	0.402	+192%	0.004	0.77%	anemometer calibration
C_V	1.000	−2.79%	0.100	0.28%	vertical reuptake
L_T	8.34mm	+9043%/m	100um	0.90%	post length
ς	2.00mm	−4717%/m	100um	0.47%	post height
L_m	3.57mm	+463%/m	500um	0.23%	side metal strip width
ϵ_{rs}	0.040	+31.1%	0.010	0.31%	test-surface emissivity
ϵ_{wt}	0.900	+14.5%	0.025	0.36%	wind-tunnel emissivity
				2.62%	combined bias uncertainty
Symbol	**Nominal**	**Sensitivity**	**Variability**	**Uncertainty**	**Component**
ω	465r/min	+0.166%/(r/min)	14r/min	2.32%	fan rotation rate
				5.32%	RSS combined uncertainty



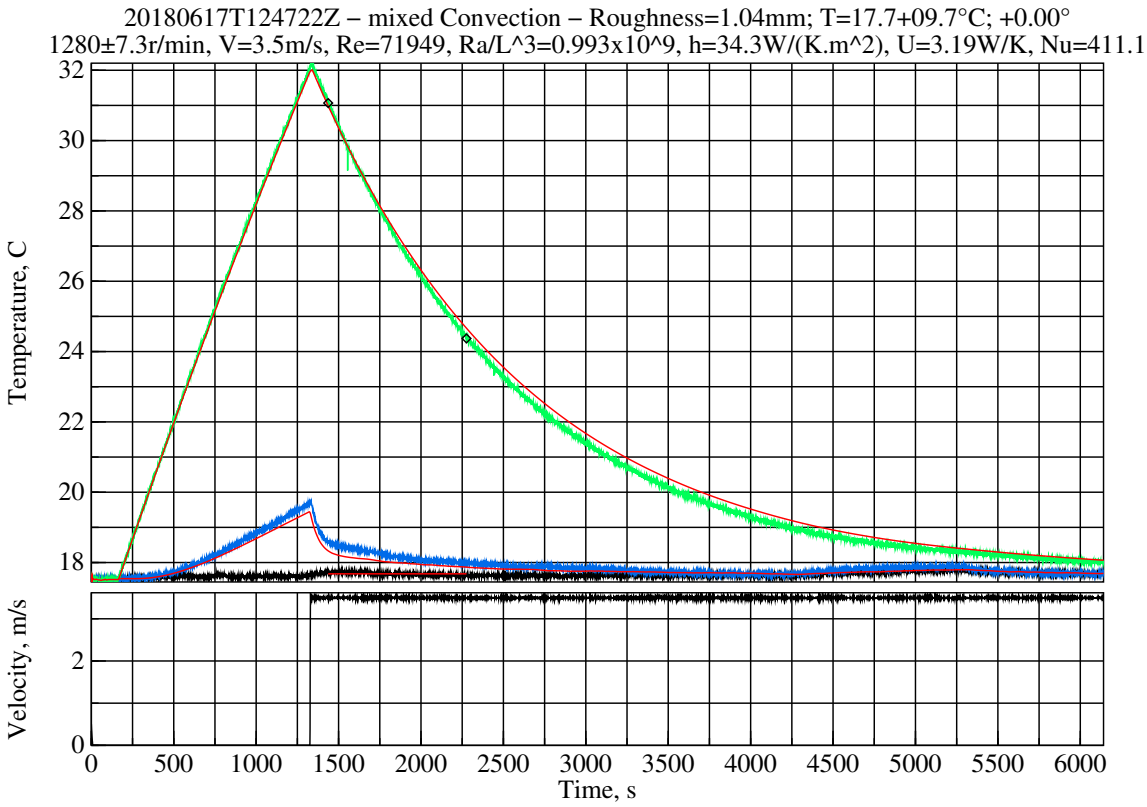
Estimated measurement uncertainties, bi-level 1mm roughness at $Re = 42969$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	10.00K	+12.0%/K	0.10K	1.20%	LM35C differential
P	101kPa	+0.0008%/Pa	1.5kPa	1.26%	MPXH6115A6U air pressure
C_{pt}	4.24kJ/K	+0.028%/(J/K)	42J/K	1.17%	plate thermal capacity
η	0.402	+173%	0.004	0.70%	anemometer calibration
u_u	5.249	+2.50%	0.100	0.25%	diffuser airflow upper bound
C_V	1.000	−2.20%	0.100	0.22%	vertical reuptake
L_T	8.34mm	+9185%/m	100um	0.92%	post length
ς	2.00mm	−3081%/m	100um	0.31%	post height
L_m	3.57mm	+456%/m	500um	0.23%	side metal strip width
ϵ_{rs}	0.040	+24.7%	0.010	0.25%	test-surface emissivity
ϵ_{wt}	0.900	+11.4%	0.025	0.29%	wind-tunnel emissivity
				2.50%	combined bias uncertainty
Symbol	**Nominal**	**Sensitivity**	**Variability**	**Uncertainty**	**Component**
ω	640r/min	+0.109%/(r/min)	4.4r/min	0.48%	fan rotation rate
				2.67%	RSS combined uncertainty



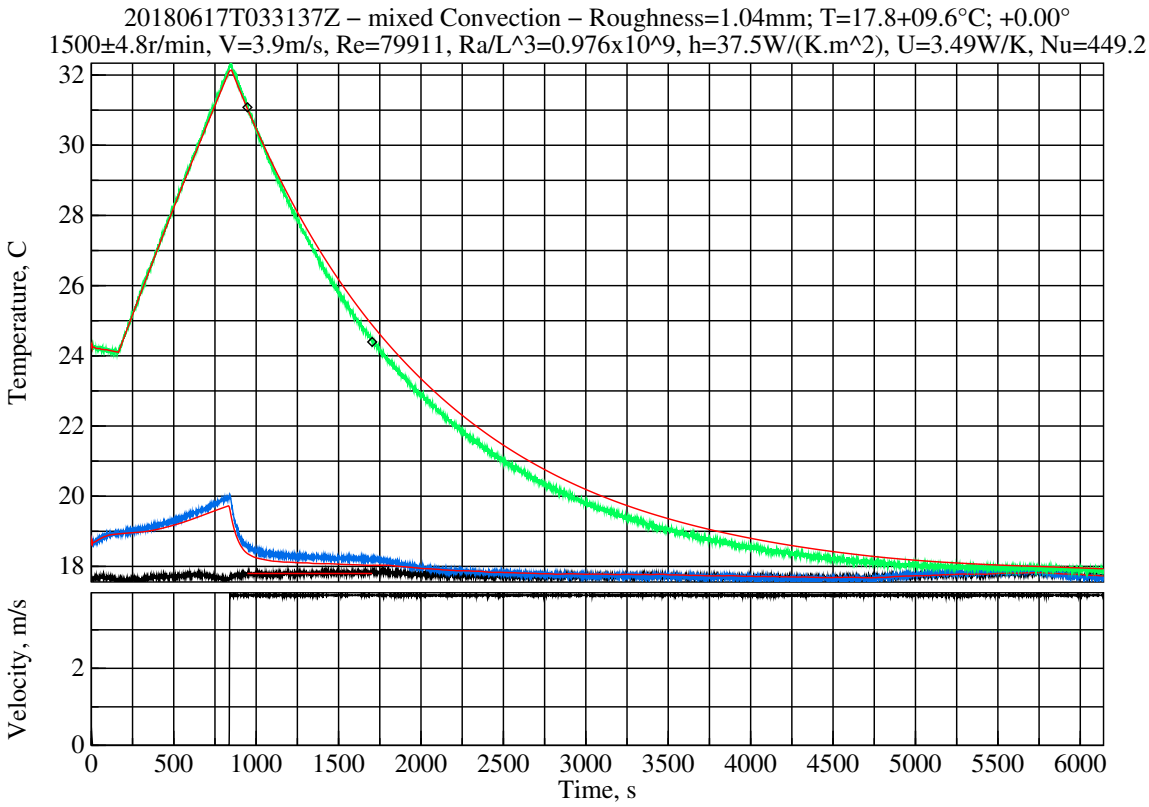
Estimated measurement uncertainties, bi-level 1mm roughness at $Re = 56627$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	9.87K	+11.8%/K	0.10K	1.18%	LM35C differential
P	101kPa	+0.0008%/Pa	1.5kPa	1.22%	MPXH6115A6U air pressure
C_{pt}	4.24kJ/K	+0.027%/(J/K)	42J/K	1.14%	plate thermal capacity
η	0.402	+146%	0.004	0.59%	anemometer calibration
u_u	5.249	+4.25%	0.100	0.42%	diffuser airflow upper bound
L_T	8.34mm	+9272%/m	100um	0.93%	post length
L_m	3.57mm	+454%/m	500um	0.23%	side metal strip width
ϵ_{wt}	0.900	+9.07%	0.025	0.23%	wind-tunnel emissivity
				2.42%	combined bias uncertainty
Symbol	**Nominal**	**Sensitivity**	**Variability**	**Uncertainty**	**Component**
ω	905r/min	+0.066%/(r/min)	6.0r/min	0.40%	fan rotation rate
				2.55%	RSS combined uncertainty



Estimated measurement uncertainties, bi-level 1mm roughness at $Re = 71950$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	9.69K	+11.7%/K	0.10K	1.17%	LM35C differential
P	101kPa	+0.0008%/Pa	1.5kPa	1.20%	MPXH6115A6U air pressure
C_{pt}	4.24kJ/K	+0.026%/(J/K)	42J/K	1.12%	plate thermal capacity
η	0.402	+111%	0.004	0.44%	anemometer calibration
u_u	5.249	+6.75%	0.100	0.68%	diffuser airflow upper bound
L_T	8.34mm	+9322%/m	100um	0.93%	post length
L_m	3.57mm	+452%/m	500um	0.23%	side metal strip width
				2.41%	combined bias uncertainty
Symbol	**Nominal**	**Sensitivity**	**Variability**	**Uncertainty**	**Component**
ω	1.28kr/min	+0.041%/(r/min)	7.3r/min	0.30%	fan rotation rate
				2.48%	RSS combined uncertainty



Estimated measurement uncertainties, bi-level 1mm roughness at $Re = 79906$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	9.59K	+11.7%/K	0.10K	1.17%	LM35C differential
P	101kPa	+0.0008%/Pa	1.5kPa	1.20%	MPXH6115A6U air pressure
C_{pt}	4.24kJ/K	+0.026%/(J/K)	42J/K	1.11%	plate thermal capacity
η	0.402	+88.9%	0.004	0.36%	anemometer calibration
u_u	5.249	+8.34%	0.100	0.83%	diffuser airflow upper bound
L_T	8.34mm	+9339%/m	100um	0.93%	post length
L_m	3.57mm	+451%/m	500um	0.23%	side metal strip width
				2.43%	combined bias uncertainty
Symbol	**Nominal**	**Sensitivity**	**Variability**	**Uncertainty**	**Component**
ω	1.50kr/min	+0.039%/(r/min)	4.8r/min	0.19%	fan rotation rate
				2.46%	RSS combined uncertainty