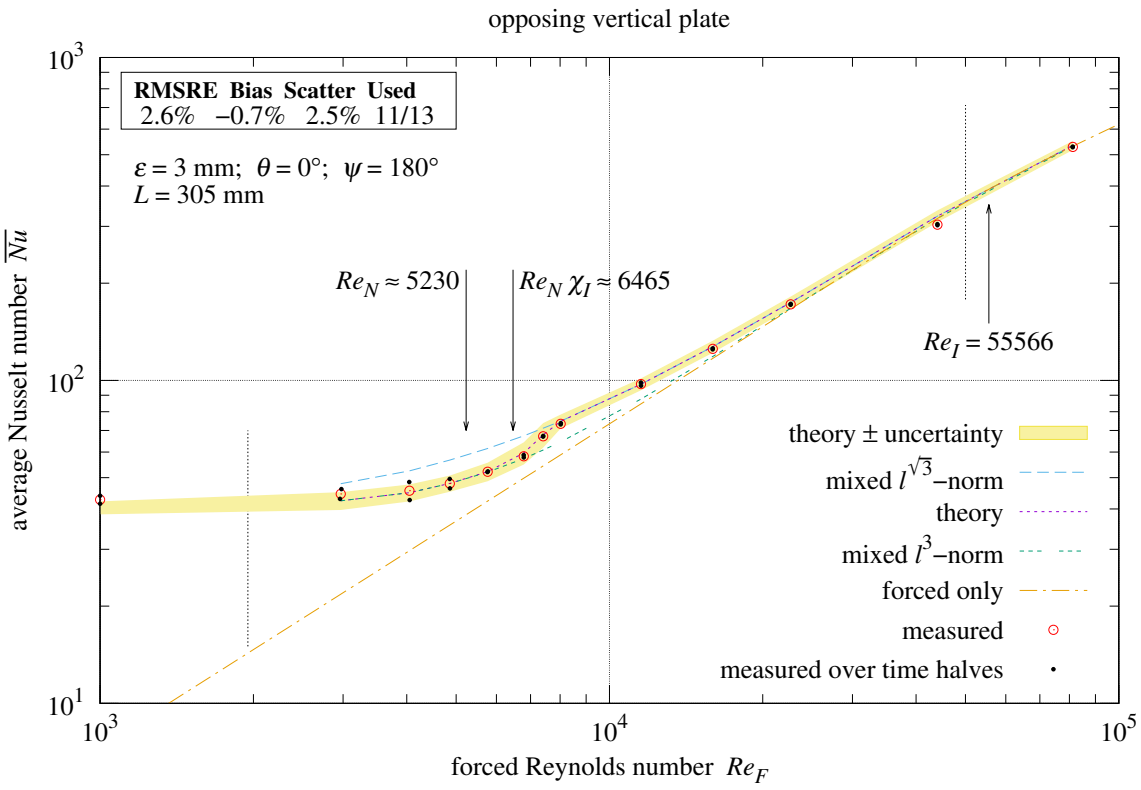
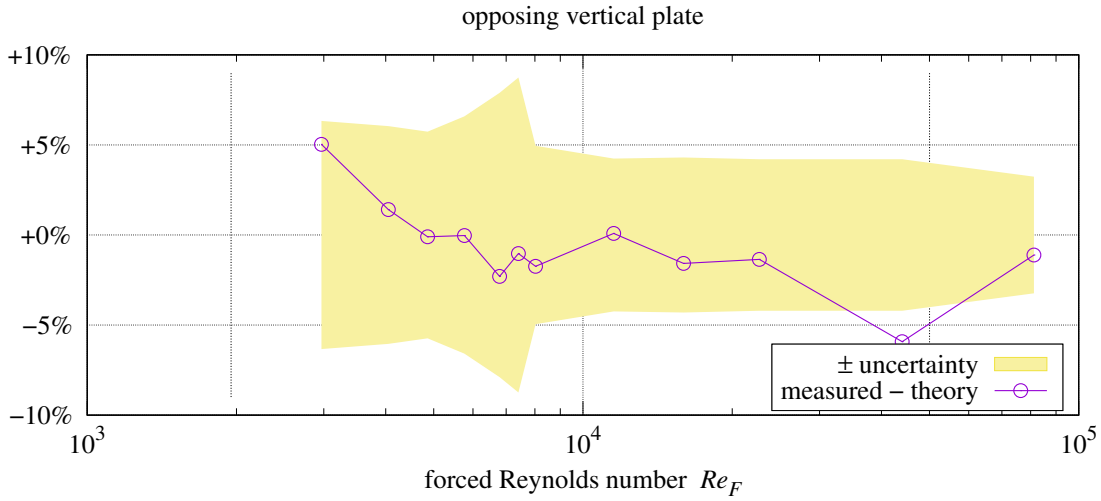
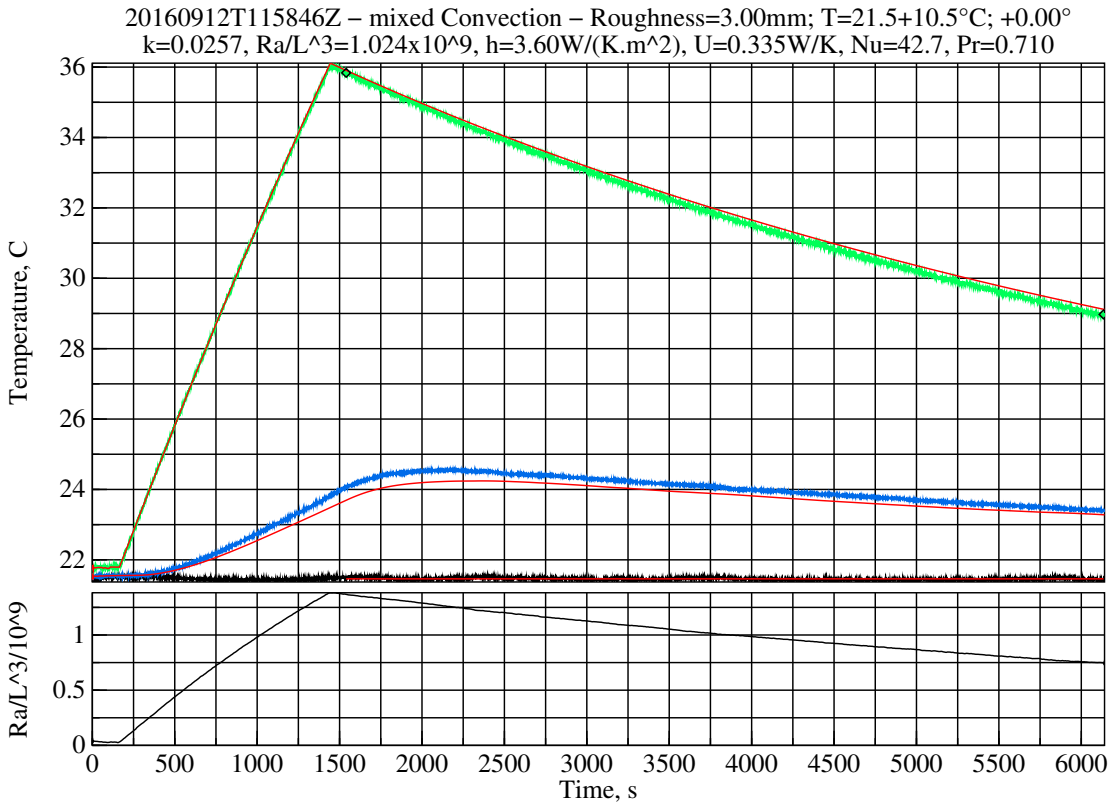
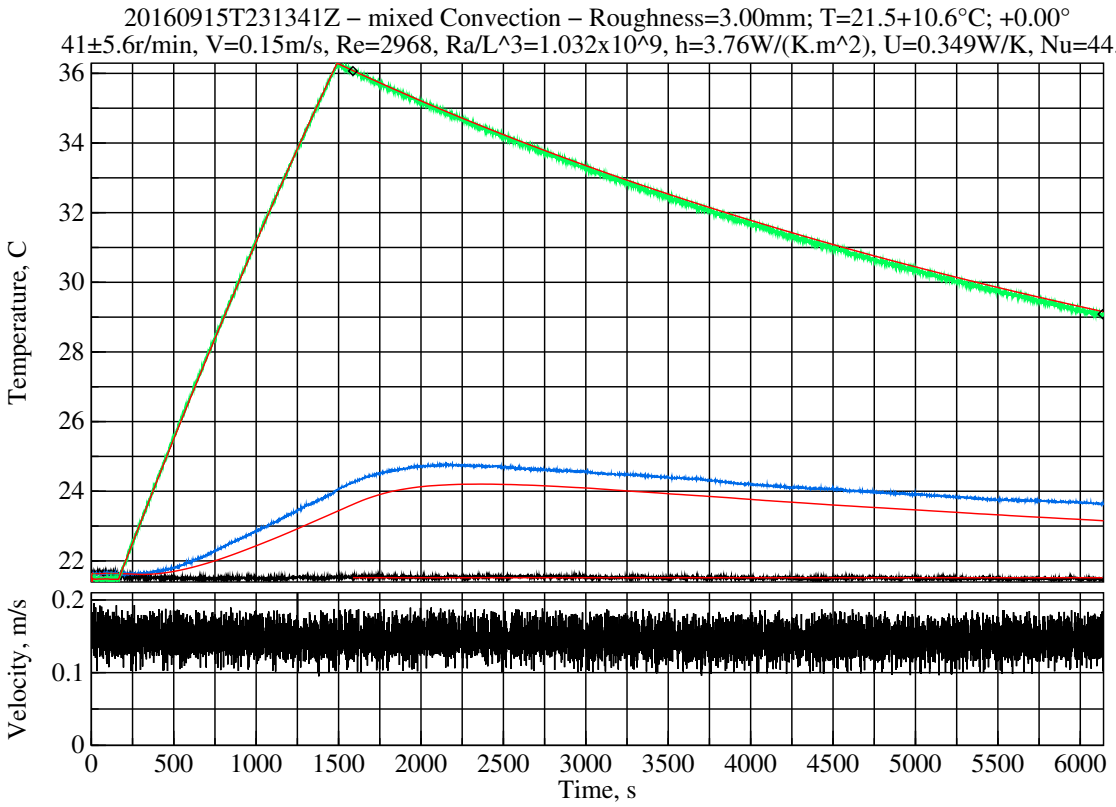

opposing vertical plate
RMSRE Bias Scatter Used
2.6% −0.7% 2.5% 11/13
ε = 3 mm; θ = 0°; ψ = 180°
L = 305 mm
Re_N ≈ 5230
Re_N χ_I ≈ 6465
Re_I = 55566
theory ± uncertainty
mixed l^√3–norm
theory
mixed l^3–norm
forced only
measured
measured over time halves
average Nusselt number Nu
forced Reynolds number Re_F


opposing vertical plate
± uncertainty
measured – theory
forced Reynolds number Re_F



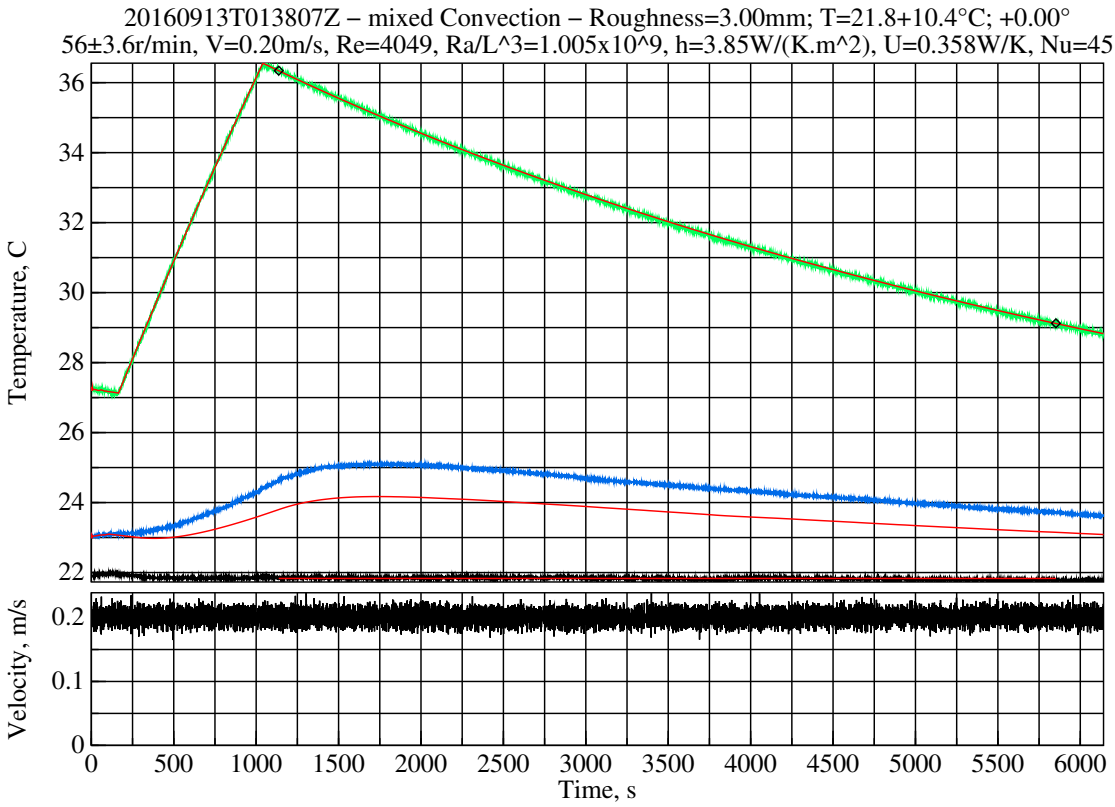
Estimated measurement uncertainties of natural convection at $\theta = 0.0$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	10.5K	+23.0%/K	0.10K	2.30%	LM35C differential
P	102kPa	+0.0007%/Pa	1.5kPa	1.03%	MPXH6115A6U air pressure
C_{pt}	4.69kJ/K	+0.044%/(J/K)	47J/K	2.06%	plate thermal capacity
C_V	1.000	−15.1%	0.100	1.51%	vertical reuptake
L_c	0.305m	+622%/m	500um	0.31%	characteristic length
D_{PIR}	25.4mm	−542%/m	1.0mm	0.54%	insulation thickness
D_g	1.00mm	−550%/m	500um	0.27%	air gap
L_m	3.57mm	+1198%/m	500um	0.60%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.524\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	0.58%	PIR thermal conductivity
ϵ_{XPS}	0.515	+38.9%	0.010	0.39%	XPS emissivity
ϵ_{tp}	0.890	+46.6%	0.015	0.70%	tape emissivity
Ω_{tp}	0.540	+31.7%	0.020	0.63%	tape coverage
ϵ_{rs}	0.040	+162%	0.010	1.62%	test-surface emissivity
ϵ_{wt}	0.900	+76.4%	0.025	1.91%	wind-tunnel emissivity
				4.63%	combined bias uncertainty



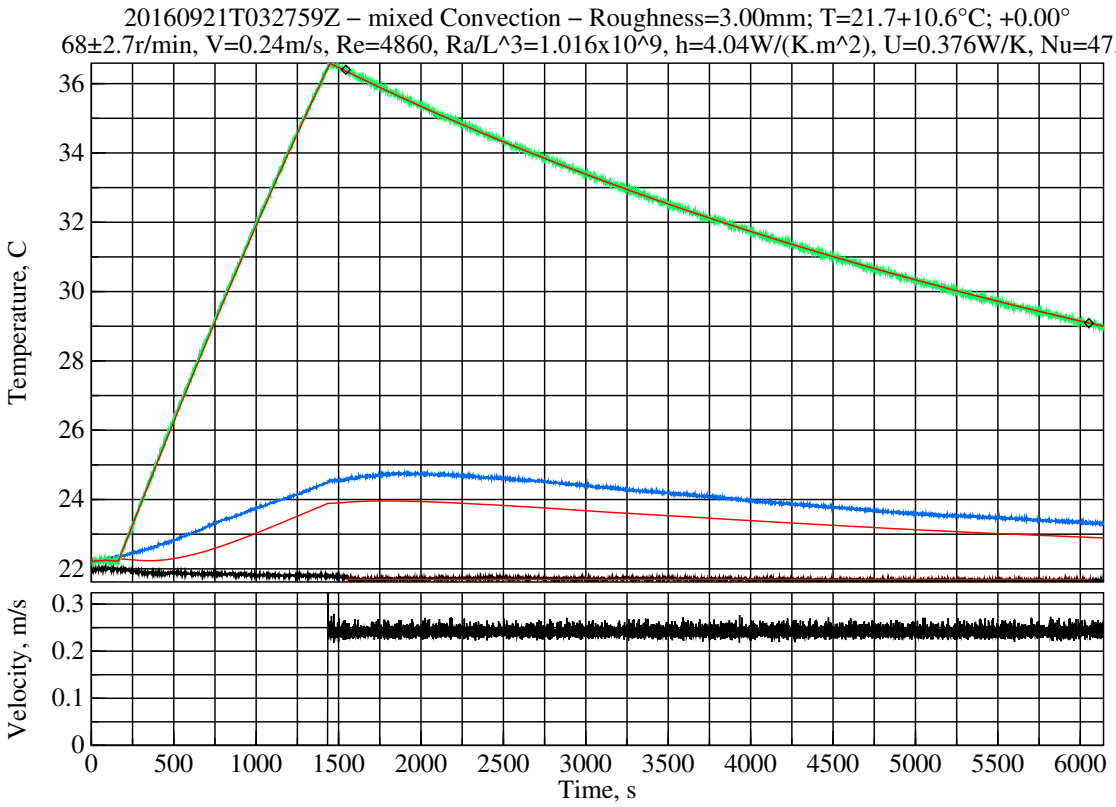
Estimated measurement uncertainties, bi-level 3mm roughness at $Re = 2968$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	10.6K	+21.9%/K	0.10K	2.19%	LM35C differential
P	102kPa	+0.0007%/Pa	1.5kPa	1.12%	MPXH6115A6U air pressure
C_{pt}	4.69kJ/K	+0.043%/(J/K)	47J/K	2.01%	plate thermal capacity
η	0.401	+40.5%	0.014	0.57%	anemometer calibration
C_V	1.000	−14.4%	0.100	1.44%	vertical reuptake
L_c	0.305m	+586%/m	500um	0.29%	characteristic length
D_{PIR}	25.4mm	−511%/m	1.0mm	0.51%	insulation thickness
D_g	1.00mm	−518%/m	500um	0.26%	air gap
L_m	3.57mm	+1205%/m	500um	0.60%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.500\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	0.55%	PIR thermal conductivity
ϵ_{XPS}	0.515	+36.9%	0.010	0.37%	XPS emissivity
ϵ_{tp}	0.890	+44.3%	0.015	0.66%	tape emissivity
Ω_{tp}	0.540	+30.1%	0.020	0.60%	tape coverage
ϵ_{rs}	0.040	+154%	0.010	1.54%	test-surface emissivity
ϵ_{wt}	0.900	+72.6%	0.025	1.81%	wind-tunnel emissivity
				4.50%	combined bias uncertainty
Symbol	**Nominal**	**Sensitivity**	**Variability**	**Uncertainty**	**Component**
ω	41.2r/min	+0.394%/(r/min)	5.6r/min	2.22%	fan rotation rate
				6.33%	RSS combined uncertainty



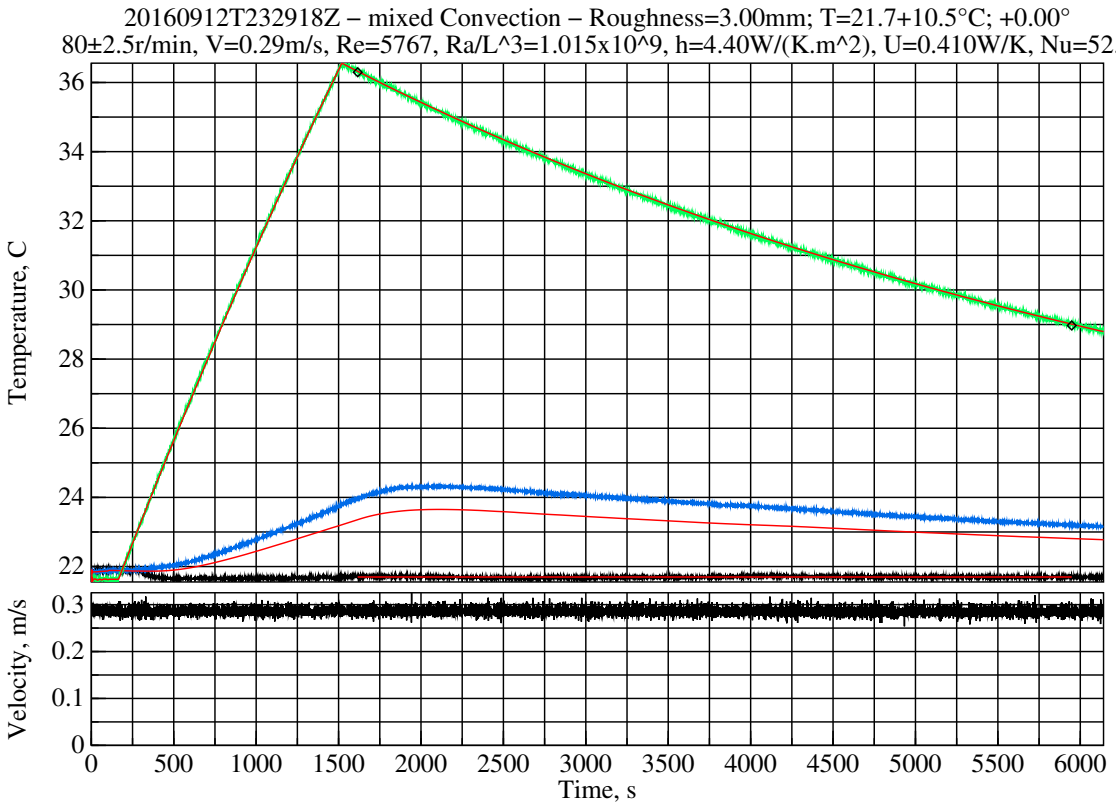
Estimated measurement uncertainties, bi-level 3mm roughness at $Re = 4049$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	10.4K	+21.3%/K	0.10K	2.13%	LM35C differential
P	101kPa	+0.0008%/Pa	1.5kPa	1.20%	MPXH6115A6U air pressure
C_{pt}	4.69kJ/K	+0.042%/(J/K)	47J/K	1.96%	plate thermal capacity
η	0.401	+78.7%	0.014	1.11%	anemometer calibration
C_V	1.000	−13.5%	0.100	1.35%	vertical reuptake
L_c	0.305m	+547%/m	500um	0.27%	characteristic length
ς	6.00mm	+2082%/m	100um	0.21%	post height
D_{PIR}	25.4mm	−519%/m	1.0mm	0.52%	insulation thickness
D_g	1.00mm	−527%/m	500um	0.26%	air gap
L_m	3.57mm	+1179%/m	500um	0.59%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.511\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	0.57%	PIR thermal conductivity
ϵ_{XPS}	0.515	+34.9%	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	+146%	0.010	1.46%	test-surface emissivity
ϵ_{wt}	0.900	+68.4%	0.025	1.71%	wind-tunnel emissivity
				4.47%	combined bias uncertainty
Symbol	**Nominal**	**Sensitivity**	**Variability**	**Uncertainty**	**Component**
ω	56.5r/min	+0.560%/(r/min)	3.6r/min	2.03%	fan rotation rate
				6.04%	RSS combined uncertainty



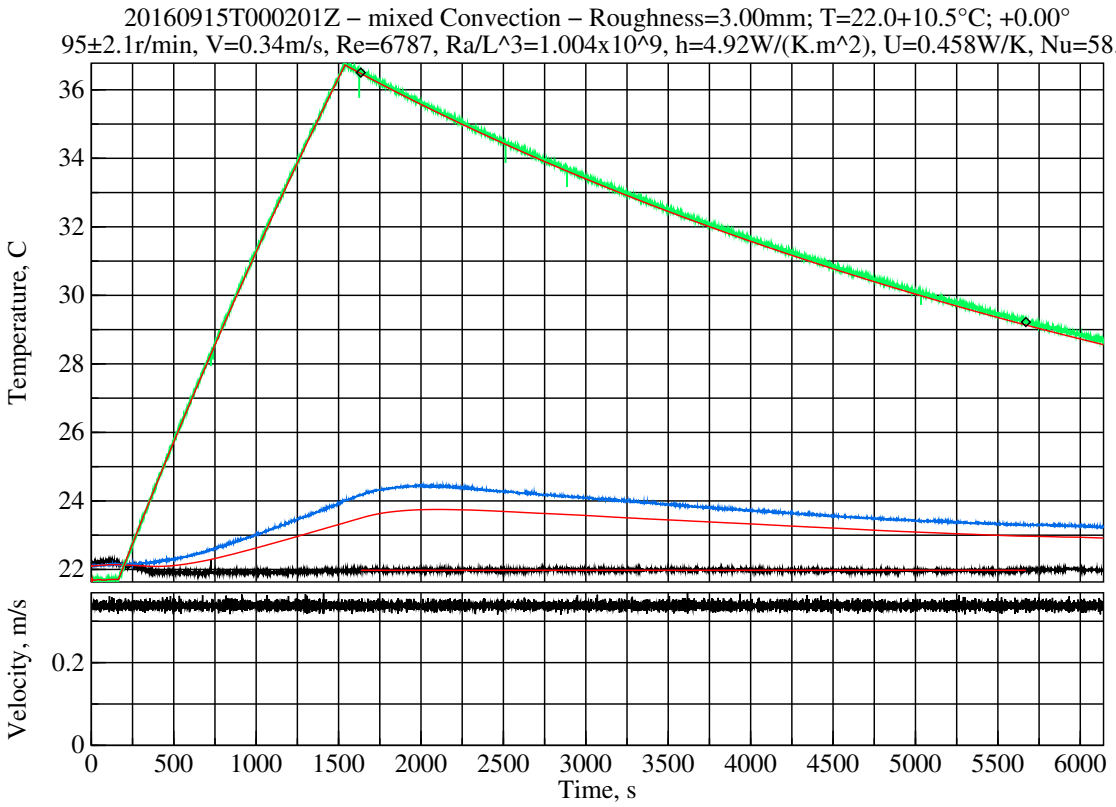
Estimated measurement uncertainties, bi-level 3mm roughness at $Re = 4860$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	10.6K	+20.1%/K	0.10K	2.01%	LM35C differential
P	101kPa	+0.0009%/Pa	1.5kPa	1.28%	MPXH6115A6U air pressure
C_{pt}	4.69kJ/K	+0.041%/(J/K)	47J/K	1.91%	plate thermal capacity
η	0.401	+112%	0.014	1.58%	anemometer calibration
C_V	1.000	−12.7%	0.100	1.27%	vertical reuptake
L_c	0.305m	+513%/m	500um	0.26%	characteristic length
ς	6.00mm	+2977%/m	100um	0.30%	post height
D_{PIR}	25.4mm	−506%/m	1.0mm	0.51%	insulation thickness
D_g	1.00mm	−513%/m	500um	0.26%	air gap
L_m	3.57mm	+1140%/m	500um	0.57%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.499\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	0.55%	PIR thermal conductivity
ϵ_{XPS}	0.515	+32.6%	0.010	0.33%	XPS emissivity
ϵ_{tp}	0.890	+39.2%	0.015	0.59%	tape emissivity
Ω_{tp}	0.540	+26.6%	0.020	0.53%	tape coverage
ϵ_{rs}	0.040	+136%	0.010	1.36%	test-surface emissivity
ϵ_{wt}	0.900	+63.8%	0.025	1.60%	wind-tunnel emissivity
				4.45%	combined bias uncertainty
Symbol	**Nominal**	**Sensitivity**	**Variability**	**Uncertainty**	**Component**
ω	67.9r/min	+0.664%/(r/min)	2.7r/min	1.81%	fan rotation rate
				5.74%	RSS combined uncertainty



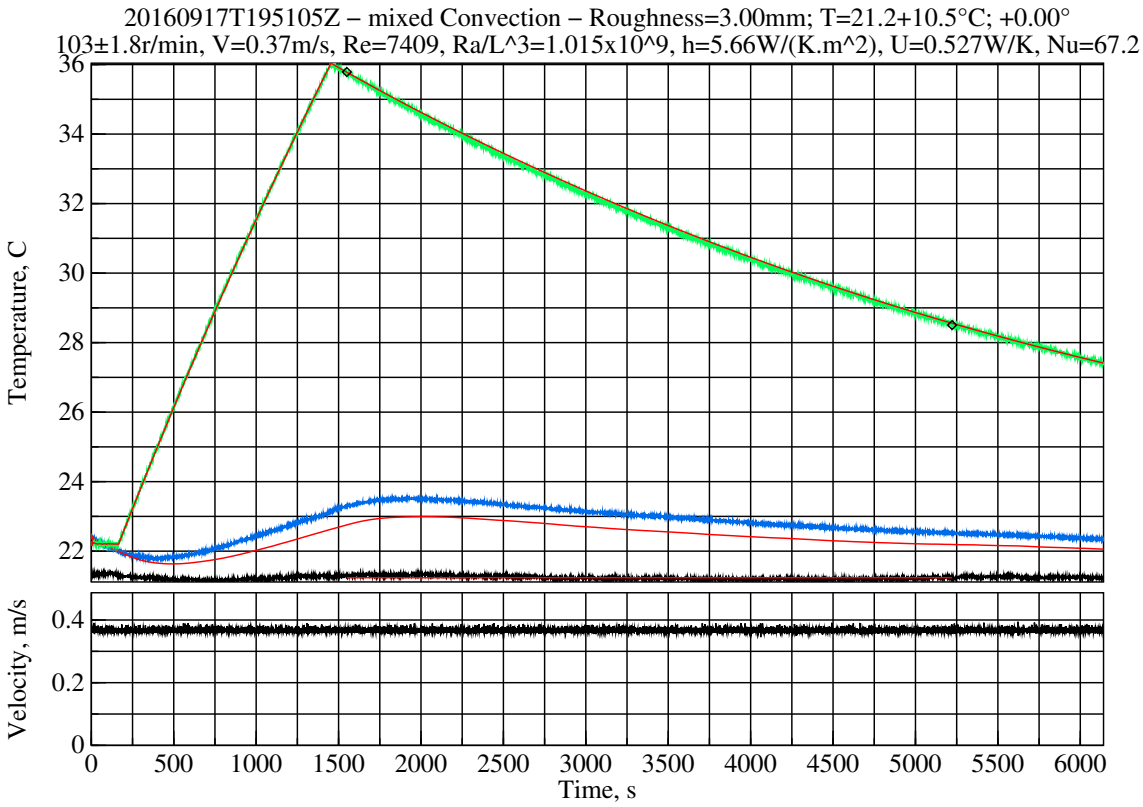
Estimated measurement uncertainties, bi-level 3mm roughness at $Re = 5767$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	10.5K	+18.9%/K	0.10K	1.89%	LM35C differential
P	101kPa	+0.0010%/Pa	1.5kPa	1.43%	MPXH6115A6U air pressure
C_{pt}	4.69kJ/K	+0.039%/(J/K)	47J/K	1.84%	plate thermal capacity
η	0.401	+178%	0.014	2.50%	anemometer calibration
C_V	1.000	−11.6%	0.100	1.16%	vertical reuptake
L_c	0.305m	+493%/m	500um	0.25%	characteristic length
ς	6.00mm	+3844%/m	100um	0.38%	post height
D_{PIR}	25.4mm	−480%/m	1.0mm	0.48%	insulation thickness
D_g	1.00mm	−487%/m	500um	0.24%	air gap
L_m	3.57mm	+1141%/m	500um	0.57%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.480\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	0.53%	PIR thermal conductivity
ϵ_{XPS}	0.515	+29.7%	0.010	0.30%	XPS emissivity
ϵ_{tp}	0.890	+35.7%	0.015	0.54%	tape emissivity
Ω_{tp}	0.540	+24.2%	0.020	0.48%	tape coverage
ϵ_{rs}	0.040	+125%	0.010	1.25%	test-surface emissivity
ϵ_{wt}	0.900	+58.2%	0.025	1.45%	wind-tunnel emissivity
θ	50.0m°	+1.89%/°	0.50°	0.95%	plate angle
				4.80%	combined bias uncertainty
Symbol	**Nominal**	**Sensitivity**	**Variability**	**Uncertainty**	**Component**
ω	80.4r/min	+0.890%/(r/min)	2.5r/min	2.26%	fan rotation rate
				6.59%	RSS combined uncertainty



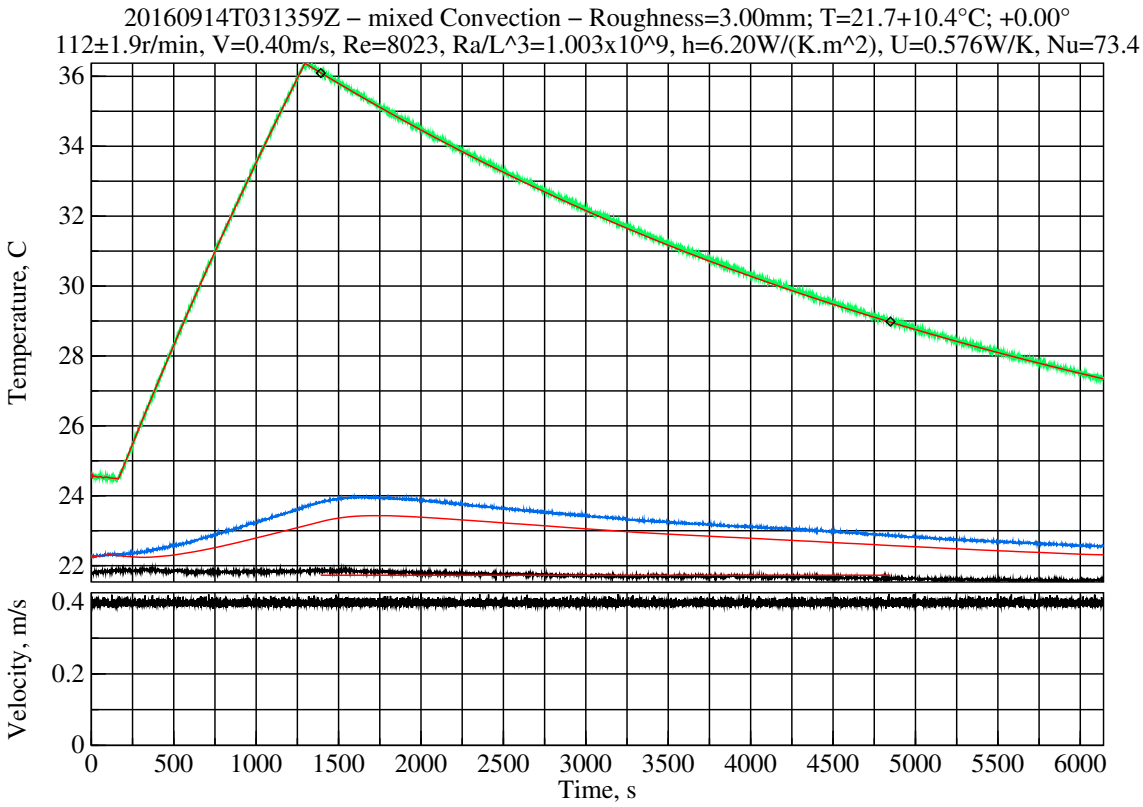
Estimated measurement uncertainties, bi-level 3mm roughness at $Re = 6788$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	10.5K	+16.7%/K	0.10K	1.67%	LM35C differential
P	101kPa	+0.0012%/Pa	1.5kPa	1.74%	MPXH6115A6U air pressure
C_{pt}	4.69kJ/K	+0.037%/(J/K)	47J/K	1.74%	plate thermal capacity
η	0.401	+308%	0.014	4.33%	anemometer calibration
C_V	1.000	−10.1%	0.100	1.01%	vertical reuptake
L_c	0.305m	+638%/m	500um	0.32%	characteristic length
ς	6.00mm	+3290%/m	100um	0.33%	post height
D_{PIR}	25.4mm	−432%/m	1.0mm	0.43%	insulation thickness
D_g	1.00mm	−438%/m	500um	0.22%	air gap
L_m	3.57mm	+1088%/m	500um	0.54%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.436\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	0.48%	PIR thermal conductivity
ϵ_{XPS}	0.515	+25.9%	0.010	0.26%	XPS emissivity
ϵ_{tp}	0.890	+31.1%	0.015	0.47%	tape emissivity
Ω_{tp}	0.540	+21.1%	0.020	0.42%	tape coverage
ϵ_{rs}	0.040	+109%	0.010	1.09%	test-surface emissivity
ϵ_{wt}	0.900	+50.6%	0.025	1.27%	wind-tunnel emissivity
				5.73%	combined bias uncertainty
Symbol	**Nominal**	**Sensitivity**	**Variability**	**Uncertainty**	**Component**
ω	95.0r/min	+1.30%/(r/min)	2.1r/min	2.71%	fan rotation rate
				7.89%	RSS combined uncertainty



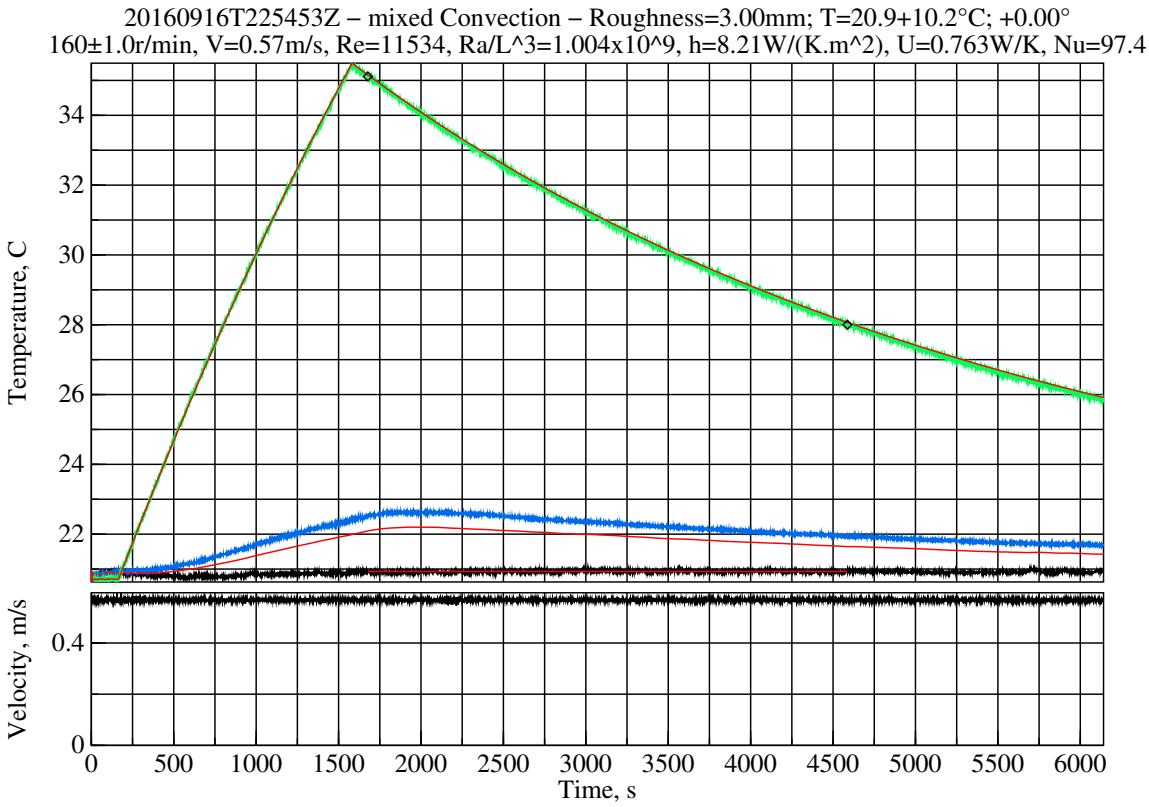
Estimated measurement uncertainties, bi-level 3mm roughness at $Re = 7410$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	10.5K	+14.8%/K	0.10K	1.48%	LM35C differential
P	101kPa	+0.0013%/Pa	1.5kPa	1.97%	MPXH6115A6U air pressure
C_{pt}	4.69kJ/K	+0.035%/(J/K)	47J/K	1.66%	plate thermal capacity
η	0.401	+407%	0.014	5.72%	anemometer calibration
C_V	1.000	−8.94%	0.100	0.89%	vertical reuptake
L_c	0.305m	+765%/m	500um	0.38%	characteristic length
ς	6.00mm	+2295%/m	100um	0.23%	post height
D_{PIR}	25.4mm	−386%/m	1.0mm	0.39%	insulation thickness
L_m	3.57mm	+976%/m	500um	0.49%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.391\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	0.43%	PIR thermal conductivity
ϵ_{XPS}	0.515	+22.6%	0.010	0.23%	XPS emissivity
ϵ_{tp}	0.890	+27.2%	0.015	0.41%	tape emissivity
Ω_{tp}	0.540	+18.4%	0.020	0.37%	tape coverage
ϵ_{rs}	0.040	+95.7%	0.010	0.96%	test-surface emissivity
ϵ_{wt}	0.900	+44.2%	0.025	1.11%	wind-tunnel emissivity
				6.76%	combined bias uncertainty
Symbol	**Nominal**	**Sensitivity**	**Variability**	**Uncertainty**	**Component**
ω	103r/min	+1.58%/(r/min)	1.8r/min	2.77%	fan rotation rate
				8.74%	RSS combined uncertainty



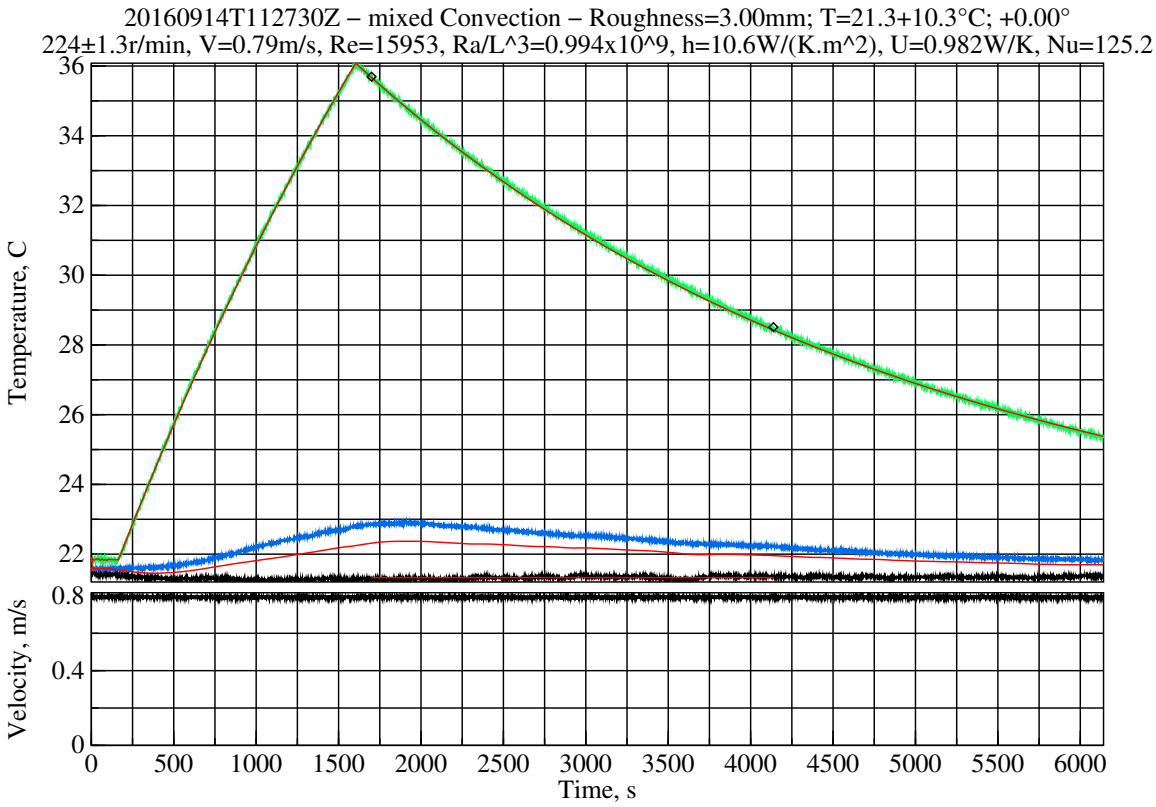
Estimated measurement uncertainties, bi-level 3mm roughness at $Re = 8022$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	10.4K	+16.5%/K	0.10K	1.65%	LM35C differential
P	101kPa	+0.0010%/Pa	1.5kPa	1.43%	MPXH6115A6U air pressure
C_{pt}	4.69kJ/K	+0.034%/(J/K)	47J/K	1.60%	plate thermal capacity
η	0.401	+189%	0.014	2.66%	anemometer calibration
C_V	1.000	−8.11%	0.100	0.81%	vertical reuptake
L_c	0.305m	+413%/m	500um	0.21%	characteristic length
ς	6.00mm	+4609%/m	100um	0.46%	post height
D_{PIR}	25.4mm	−355%/m	1.0mm	0.36%	insulation thickness
L_m	3.57mm	+910%/m	500um	0.46%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.360\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	0.40%	PIR thermal conductivity
ϵ_{XPS}	0.515	+20.6%	0.010	0.21%	XPS emissivity
ϵ_{tp}	0.890	+24.8%	0.015	0.37%	tape emissivity
Ω_{tp}	0.540	+16.8%	0.020	0.34%	tape coverage
ϵ_{rs}	0.040	+87.4%	0.010	0.87%	test-surface emissivity
ϵ_{wt}	0.900	+40.4%	0.025	1.01%	wind-tunnel emissivity
				4.23%	combined bias uncertainty
Symbol	**Nominal**	**Sensitivity**	**Variability**	**Uncertainty**	**Component**
ω	112r/min	+0.676%/(r/min)	1.9r/min	1.28%	fan rotation rate
				4.95%	RSS combined uncertainty



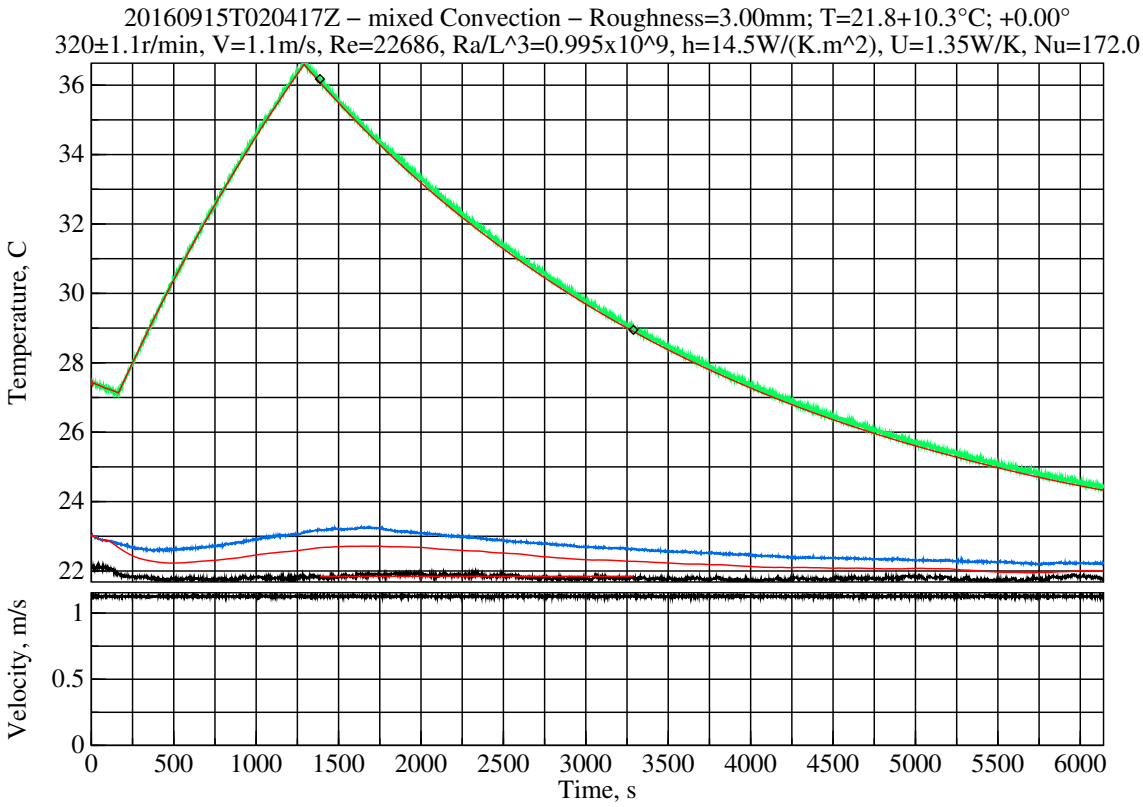
Estimated measurement uncertainties, bi-level 3mm roughness at $Re = 11534$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	10.2K	+15.2%/K	0.10K	1.52%	LM35C differential
P	102kPa	+0.0010%/Pa	1.5kPa	1.44%	MPXH6115A6U air pressure
C_{pt}	4.69kJ/K	+0.031%/(J/K)	47J/K	1.46%	plate thermal capacity
η	0.401	+204%	0.014	2.86%	anemometer calibration
C_V	1.000	−6.20%	0.100	0.62%	vertical reuptake
ς	6.00mm	+5769%/m	100um	0.58%	post height
D_{PIR}	25.4mm	−286%/m	1.0mm	0.29%	insulation thickness
L_m	3.57mm	+775%/m	500um	0.39%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.292\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	0.32%	PIR thermal conductivity
ϵ_{tp}	0.890	+18.7%	0.015	0.28%	tape emissivity
Ω_{tp}	0.540	+12.7%	0.020	0.25%	tape coverage
ϵ_{rs}	0.040	+66.2%	0.010	0.66%	test-surface emissivity
ϵ_{wt}	0.900	+30.4%	0.025	0.76%	wind-tunnel emissivity
				4.13%	combined bias uncertainty
Symbol	**Nominal**	**Sensitivity**	**Variability**	**Uncertainty**	**Component**
ω	160r/min	+0.511%/(r/min)	0.95r/min	0.49%	fan rotation rate
				4.24%	RSS combined uncertainty



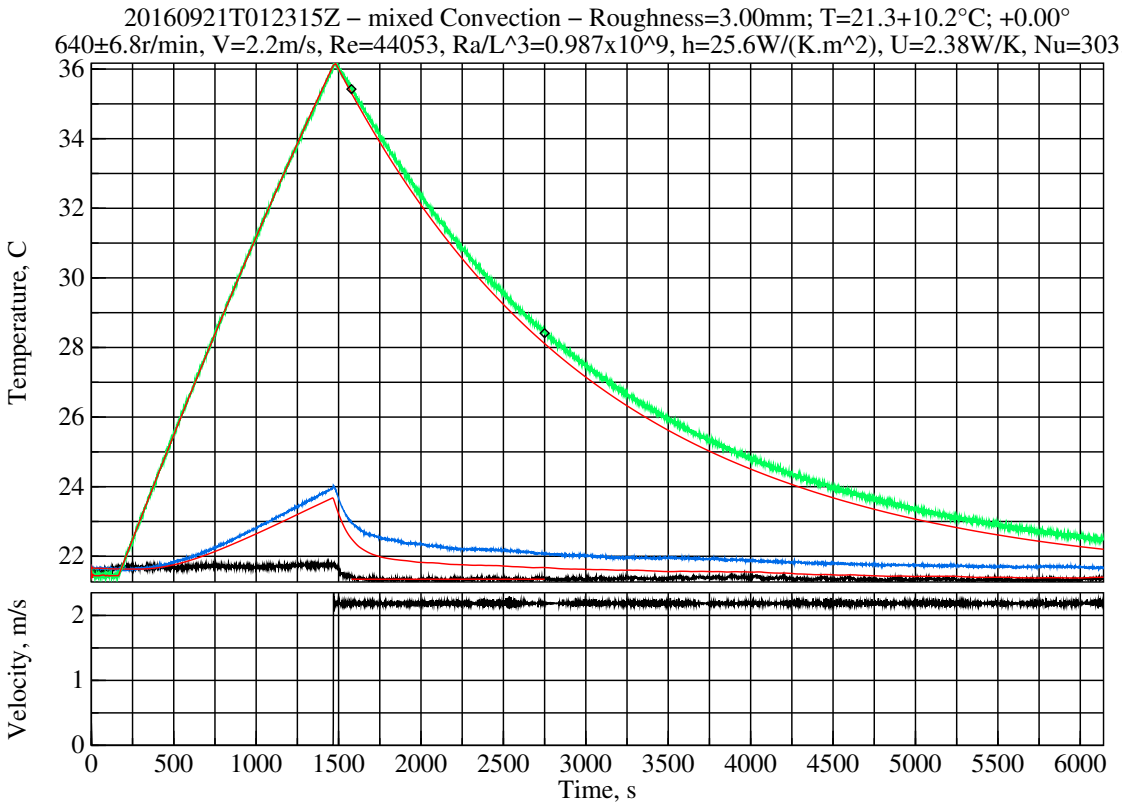
Estimated measurement uncertainties, bi-level 3mm roughness at $Re = 15953$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	10.3K	+13.8%/K	0.10K	1.38%	LM35C differential
P	101kPa	+0.0010%/Pa	1.5kPa	1.48%	MPXH6115A6U air pressure
C_{pt}	4.69kJ/K	+0.029%/(J/K)	47J/K	1.35%	plate thermal capacity
η	0.401	+224%	0.014	3.14%	anemometer calibration
C_V	1.000	−4.69%	0.100	0.47%	vertical reuptake
ς	6.00mm	+6395%/m	100um	0.64%	post height
D_{PIR}	25.4mm	−225%/m	1.0mm	0.23%	insulation thickness
L_m	3.57mm	+665%/m	500um	0.33%	side metal strip width
k_{PIR}	$22.2\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$+0.231\%/\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	$1.1\frac{\mathrm{mW}}{\mathrm{K\cdot m}}$	0.26%	PIR thermal conductivity
ϵ_{tp}	0.890	+14.2%	0.015	0.21%	tape emissivity
ϵ_{rs}	0.040	+50.4%	0.010	0.50%	test-surface emissivity
ϵ_{wt}	0.900	+23.1%	0.025	0.58%	wind-tunnel emissivity
				4.17%	combined bias uncertainty
Symbol	**Nominal**	**Sensitivity**	**Variability**	**Uncertainty**	**Component**
ω	224r/min	+0.401%/(r/min)	1.3r/min	0.52%	fan rotation rate
				4.30%	RSS combined uncertainty



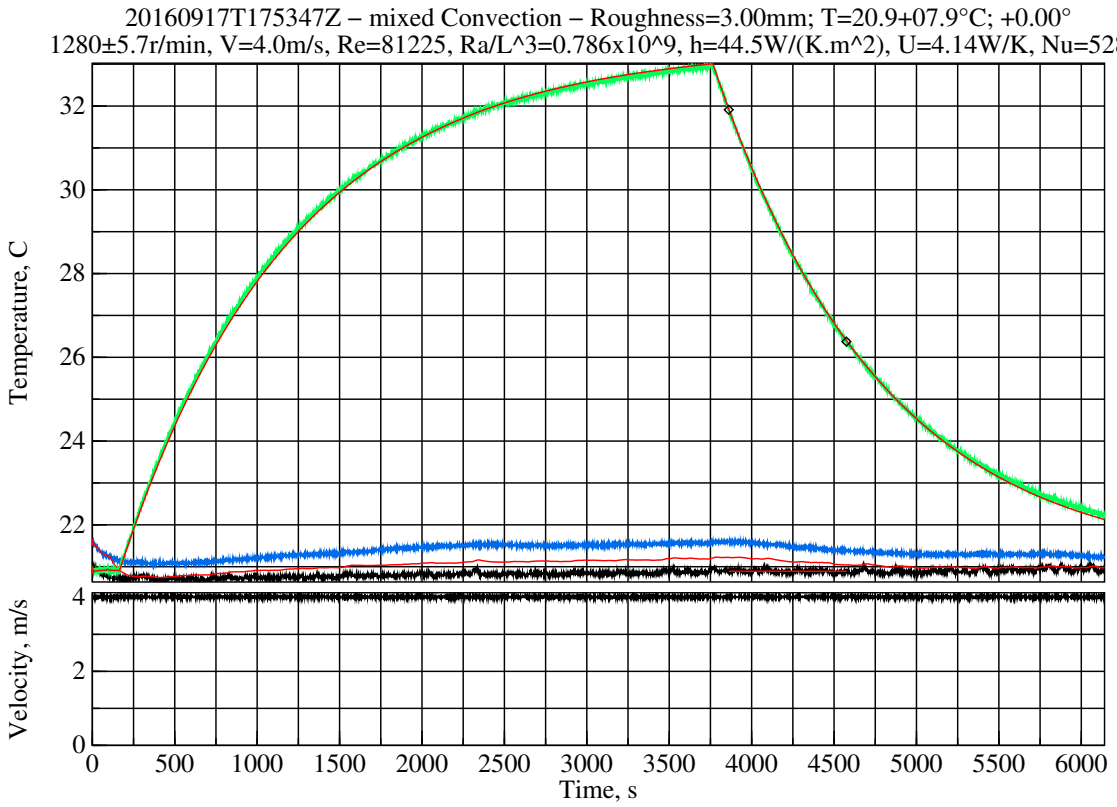
Estimated measurement uncertainties, bi-level 3mm roughness at $Re = 22686$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	10.3K	+12.6%/K	0.10K	1.26%	LM35C differential
P	101kPa	+0.0010%/Pa	1.5kPa	1.49%	MPXH6115A6U air pressure
C_{pt}	4.69kJ/K	+0.027%/(J/K)	47J/K	1.26%	plate thermal capacity
η	0.401	+233%	0.014	3.27%	anemometer calibration
C_V	1.000	−3.39%	0.100	0.34%	vertical reuptake
ς	6.00mm	+6837%/m	100um	0.68%	post height
L_m	3.57mm	+560%/m	500um	0.28%	side metal strip width
ϵ_{rs}	0.040	+36.6%	0.010	0.37%	test-surface emissivity
ϵ_{wt}	0.900	+16.7%	0.025	0.42%	wind-tunnel emissivity
				4.16%	combined bias uncertainty
Symbol	**Nominal**	**Sensitivity**	**Variability**	**Uncertainty**	**Component**
ω	320r/min	+0.292%/(r/min)	1.1r/min	0.32%	fan rotation rate
				4.20%	RSS combined uncertainty



Estimated measurement uncertainties, bi-level 3mm roughness at $Re = 44051$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	10.2K	+11.5%/K	0.10K	1.15%	LM35C differential
P	101kPa	+0.0009%/Pa	1.5kPa	1.40%	MPXH6115A6U air pressure
C_{pt}	4.69kJ/K	+0.024%/(J/K)	47J/K	1.14%	plate thermal capacity
η	0.401	+211%	0.014	2.97%	anemometer calibration
ς	6.00mm	+8940%/m	100um	0.89%	post height
L_m	3.57mm	+424%/m	500um	0.21%	side metal strip width
ϵ_{wt}	0.900	+8.77%	0.025	0.22%	wind-tunnel emissivity
				3.80%	combined bias uncertainty
Symbol	**Nominal**	**Sensitivity**	**Variability**	**Uncertainty**	**Component**
ω	640r/min	+0.133%/(r/min)	6.8r/min	0.90%	fan rotation rate
				4.20%	RSS combined uncertainty



Estimated measurement uncertainties, bi-level 3mm roughness at $Re = 81229$.

Symbol	Nominal	Sensitivity	Bias	Uncertainty	Component
ΔT	7.93K	+13.9%/K	0.10K	1.39%	LM35C differential
P	101kPa	+0.0008%/Pa	1.5kPa	1.16%	MPXH6115A6U air pressure
C_{pt}	4.69kJ/K	+0.023%/(J/K)	47J/K	1.09%	plate thermal capacity
η	0.401	+141%	0.014	1.98%	anemometer calibration
u_u	7.787	+2.63%	0.100	0.26%	diffuser airflow upper bound
ς	6.00mm	+12419%/m	100um	1.24%	post height
				3.18%	combined bias uncertainty
Symbol	**Nominal**	**Sensitivity**	**Variability**	**Uncertainty**	**Component**
ω	1.28kr/min	+0.052%/(r/min)	5.7r/min	0.30%	fan rotation rate
				3.24%	RSS combined uncertainty