

Infrared image processing for local convective heat transfer measurements in rib-enhanced channels

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Abstract. In the context of an experimental study designed to retrieve the local heat transfer characteristics in closed channels with ribs in several configurations by IR thermography, a filtering strategy must be adopted to calculate the laplacian of the temperature field, to remove not only Gaussian noise, but also unwanted local features due to the pattern of the conductors of the heater. In this paper, these issues are addressed with a comparative analysis on filtering and interpolation techniques, in particular mean filtering, local surface fitting and cubic smoothing splines, which are carried out by showing their influence on the smoothed thermogram and on the laplacian of the temperature field. The use of cubic smoothing splines gives the best approximation of the temperature field with respect to the mean filter, which alters the temperature field in proximity of the ribs, and to surface interpolation. However, the only filter among those tried that gives meaningful derivatives on the whole image is the mean filter, with a kernel size equal or bigger to that of the spatial feature to be filtered. The resulting derivative also need further filtering to reduce local spikes induced by the filtering operations.

1 Introduction

A long-term investigation on convective heat transfer enhancement in rectangular channels by means of ribs, in a variety of configurations, is ongoing at the ThermALab laboratory of Politecnico di Milano, focusing both on global performances, from an experimental standpoint, and on local characteristics, by means of experimental and numerical methods, with the aim of identifying design criteria by understanding the link between flow structures and heat transfer, and to find a link between different configurations which provide similar heat transfer and pressure drop performances, as described in [1]. In this framework, a method based on IR-thermography measurements and mathematical models to retrieve the local convective heat transfer coefficient inside rectangular channels with various rib geometries and imposed heat flux on one surface has been developed and is under refinement. The method is thoroughly explained in [2] and [3].

The main difference with respect to established methods [4], which generally use 1D analytical models to solve the energy balance over a heated thin foil sensor (equation 1), consists in coupling the experimental measurements with a 2D conductive FEM model and a 2D radiative model for semi-transparent enclosures to retrieve the backside conductive heat flux $q''_{k,back}(y, z)$ and the radiative heat flux $q''_{rad}(y, z)$, respectively, for each spanwise discretized coordinate along the flow direction. Finally, the planar conductive term $q''_{k,PCB}(y, z)$ of the energy balance has to be retrieved by calculating the laplacian of the surface temperature, assumed uniform in the thickness of the conductive copper layer.



$$q_c''(y, z) = \sigma_{el} s_{Cu} - q_{rad}''(y, z) - q_{k,back}''(y, z) + q_{k,PCB}''(y, z) \quad (1)$$

This method, while more complex, allows a much better estimation of the backside conductive heat flux, which is physically minimized by insulating the bottom of the heater with air, but inevitably rises towards the contact point between the heater and its supports, and the fine calculation of the radiative component, which is affected by the presence of a spectral-selective germanium window. The planar conduction term $q_{k,PCB}''(y, z)$, which is proportional to the temperature laplacian as reported in equation 2, is not usually considered in similar experiments for higher Re [5], but becomes relevant whenever the local convective heat transfer is low, i.e. at low/transitioning flow regimes and near stagnation points, as recently discussed by Sarkar et al. [6], and by Torre et al. [7].

In this context, the thermographic image in figure 1 shows clearly that the small separation (0.2 mm between each 7.8 mm wide track) of the heater's copper tracks with an insulating material causes local increments of the thermal resistance in spanwise direction, thus causing the temperature trend to follow the geometrical features in a sort of "stairway" pattern in spanwise-y direction. Thus, to calculate the laplacian term in such direction, either the image processing algorithm should identify the regions with different conductivity to separately calculate the local resulting heat flux, or one "equivalent" directional conductivity value can be used, provided that the temperature profile is fitted to simulate its trend as if the heater had uniform properties in a given direction. For the latter strategy, which is at the moment adopted, the filtering strategy should not only reduce noise, e.g. by averaging multiple acquisitions and with Gaussian filtering, as suggested in [4], or by using Wiener filters, as done by Rainieri et al. in [8] and [9], but also suppress the unwanted local features without sacrificing the physical significance.

$$q_{k,PCB}''(y, z) = k_y s_{Cu} \left(\frac{\partial^2 T_w}{\partial y^2} \right) + k_z s_{Cu} \left(\frac{\partial^2 T_w}{\partial z^2} \right) \quad (2)$$

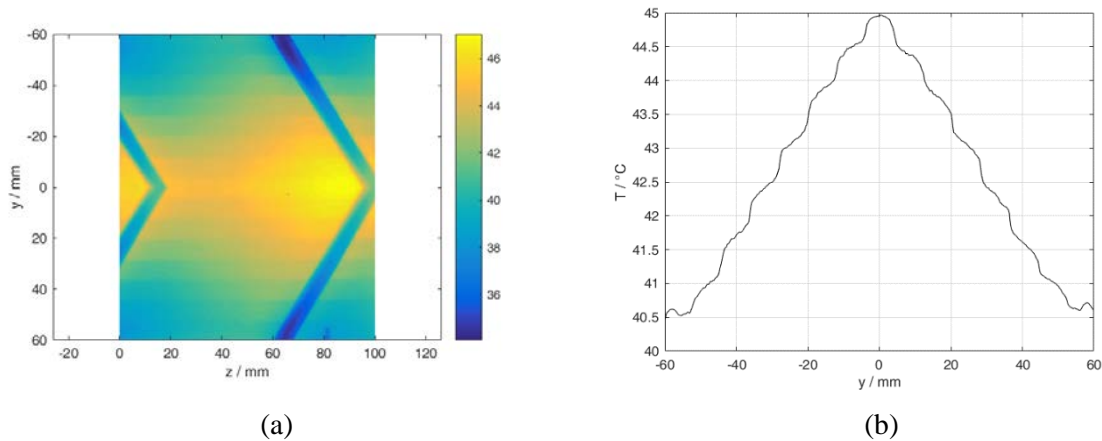


Figure 1. Thermogram of the V-down configuration, Re = 5400 (a) and spanwise – y temperature profile at z = 44 mm

The filtering strategies adopted in previous papers developed at ThermoALab [2] and [3] relied on interpolations on the whole surface or line-by-line, which can be easily carried out when the region under study is regular, i.e. not crossed by obstacles like oblique ribs which divide the temperature field in non-connected regions. However, for rib shapes like the V shown in figure 1, such regions may be small enough that a single artifact, or a marker like the one visible for z = 80 mm in figure 1, could cause significant alterations of the interpolating surface if carried on only one sub-region, while the surface interpolation of the whole thermogram does not take into account the possibility of discontinuities of

the temperature field across a rib. Moreover, the degree of the polynomial of choice dictates the shape of the curve of the second derivative, which can create non-physical results.

While the relative magnitude of the laplacian term in the energy balance is not particularly significant, i.e. around 7 % of the dissipated input heat at low Reynold number, $Re = 700$, for this series of experiments, it is still worthy to investigate a filtering strategy to estimate it in this setup, both because its miscalculation or neglect can easily raise the experimental uncertainty, and because such heat source can also be used in experiments where the laplacian term could be even more important with respect to the others, e.g. for natural convection studies or transient analyses carried out with a similar heater. In this regard, this paper describes how different image processing techniques affect the calculation of the planar conductive heat flux, and its influence on the local convective heat transfer values. The benchmark case is the chevron “V-down” configuration at $Re=5400$.

2 Materials and methods

2.1 Experimental apparatus

The measurements have been carried out on an open-loop channel operated in suction, shown in figure 1. Summarizing its main features, the channel lower surface is heated by means of two Printed Circuit Boards (PCBs) independently powered and controlled. The PCBs have a substrate made of FR-4 fiberglass-reinforced epoxy laminate material, whereas copper tracks are 0.017 mm thick, 7.8 mm wide, spaced 0.2 mm apart each other, and covered by a black lacquer which also fills up the gaps between them, making the heating surface flat, smooth and with a high emissivity. A double-glazing 130 mm x 130 mm germanium window grants the optical access to a FLIR T650sc IR-camera, with a 640 x 480-pixel resolution and a 20 mK NETD at 30 °C. The main experimental features are listed in table 1.

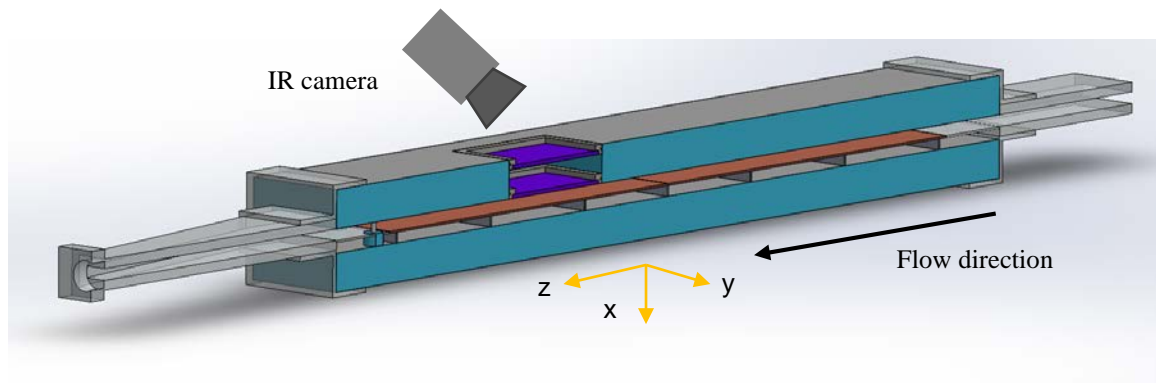


Figure 2. Lengthwise section of the test channel for local heat transfer measurements

Table 1. Main experimental features

h	Channel height	12 mm
L	Channel length	840 mm
w	Channel width	120 mm
D_h	Hydraulic diameter	21.82 mm
	Height to width ratio	0.10
s	Rib side dimension	4 mm
d	Distance rib-to-rib	80 mm
Re	Reynolds number	$700 \div 8000$

2.2 Image processing techniques

At first, the thermographic sequence of 30 images over a 1 s acquisition time is averaged point-to-point, to reduce noise. The calibration is applied on resulting thermogram, to obtain precise temperature data, then the image undergoes a projective transformation, to obtain a 2D temperature field of the channel surface under investigation. The rib-region is masked to remove their apparent temperature values from the subsequent image processing procedures. The following processing stage is intended to smooth the irregular temperature trend caused by the copper tracks. To this end, three strategies have been tested, i.e. a mean filter, a surface fitting, and the use of cubic smoothing splines, which are implemented as follows.

The mean filter replaces the temperature values with the mean over a moving window, whose size is user-defined. At the edges of the image matrix, where a full rectangle cannot be built, the portion of rectangle that fits on the image matrix is used. The same applies at the rib edges, which are replaced by Not-a-Number values. The window has been chosen after preliminary trials to be 4.67 mm x 11.33 mm, in particular the track-cancelling effect is efficiently obtained only for a spanwise window size above the width of the copper tracks, i.e. 7.8 mm. The resulting temperature field should also be differentiated twice, for the calculation of the laplacian heat flux. According to O'Hare [10], "for the n -th derivative, use at least $n+1$ applications of a rectangular smooth". In the case under analysis, a non-noisy trend of the second derivative in most of the thermograms is given by four consecutive iteration of the described mean filter.

The surface fitting is applied separately on each connected region of the thermogram, i.e. each region separated by ribs is treated as a separated polynomial. This choice should ensure the consistency of the resulting temperature field with the physical separation of the flow regions given by the ribs, and the consequent discontinuous temperature trends across the rib themselves. The results in the next paragraph are relative to a polynomial surface with order 5, both in streamwise and spanwise directions.

The final considered smoothing technique considered is the cubic smoothing spline, which is implemented in Matlab® with a routine called CSAPS. This method features a smoothing parameter p between 0 and 1 which regulates how close the spline follows the original trend: for $p = 0$, the interpolant is the least-squares straight line fit to the data, for $p = 1$, the result is the variational, or natural, cubic spline interpolant. In this case, $p = 1e-4$ for the thermogram in pixel (non-physical) coordinates. This approach is used for each pixel in the spanwise direction.

3 Results

3.1 Temperature field

All the three reported smoothing methods achieve the objective of filtering the local features given by the copper tracks. However, each of them has some drawbacks, which are visible in figures 3-4. In particular, the 4-times mean filter lowers the peak temperature values in the middle streamwise region of around 0.5 °C, and has the tendency to alter significantly the values in proximity of the ribs. Local unwanted features, like dust grains (e.g. at $y = 3$ mm, $z = 66$ mm) or local markers (at $y = 60$ mm, $z = 80$ mm) are effectively filtered. The surface fitting method on connected regions shows the highest discrepancies towards the tip of the left rib, and presents a more irregular difference pattern. Again, local unwanted features are of course filtered, but at the cost of altering the shape of the surface in the bottom-right region, thus causing a slight asymmetry between the top-right and the bottom-right region. Finally, the spanwise cubic smoothing spline presents a good fit of the original data while smoothing the copper tracks. It is however less effective in smoothing local defects, given the tendency to follow the original data. In particular, the method show a good data fitting over the central track, $y = 0$ mm, where the other two methods cause a decrease of temperature of about 0.5 °C.

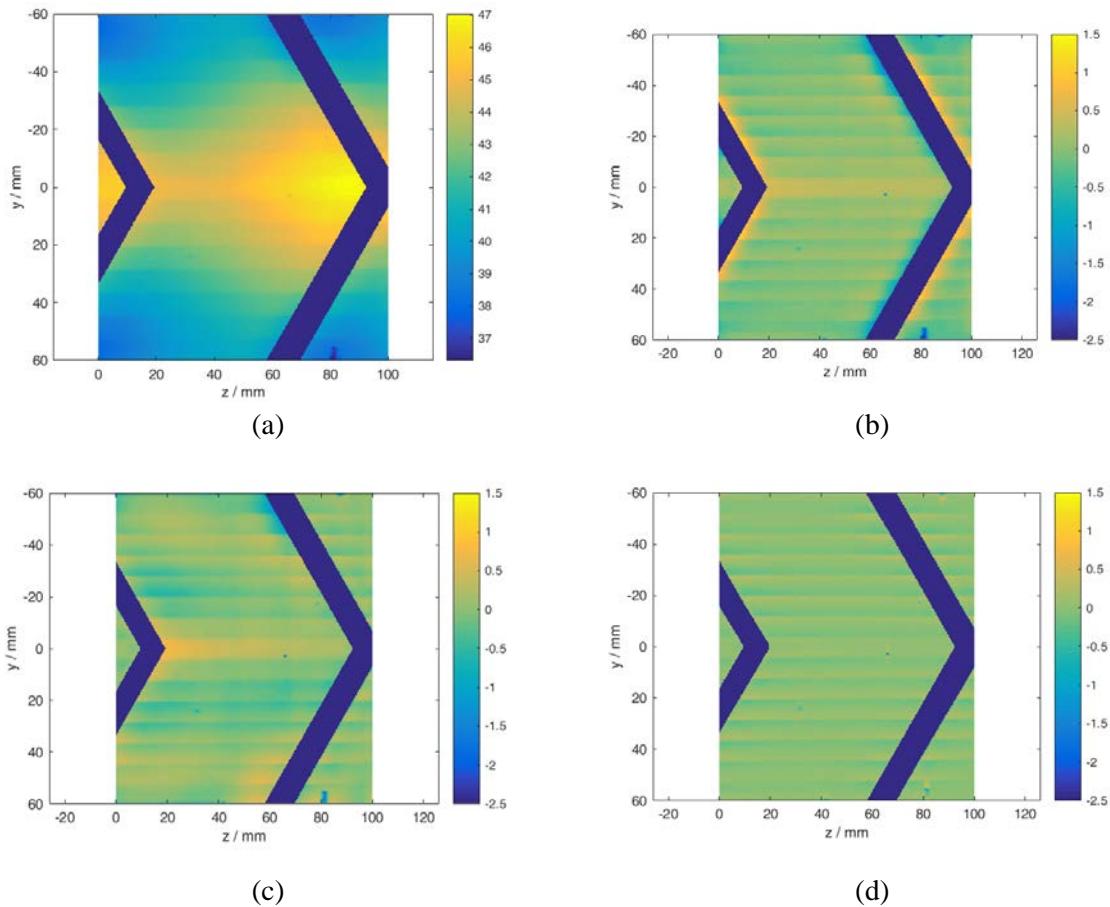


Figure 3. Temperature differences from original thermographic image (a): Mean filter (b), Surface fitting (c) and cubic smoothing spline (d).

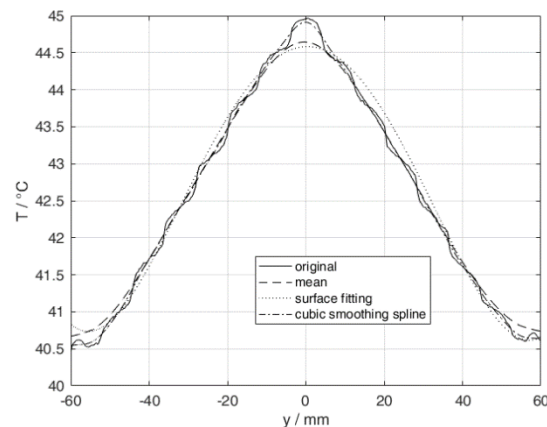


Figure 4. Filtering strategies, confrontation of temperature values with various smoothing schemes, $z = 44$ mm

3.2 2^{nd} order derivative

While the temperature values are needed to calculate the radiative heat flux and the heat flux towards the backside of the copper tracks with appropriate models, the 2^{nd} order derivative allows the calculation of the conductive heat flux across the surface, i.e. laplacian term, as equation 2.

In particular, since the method for solving the heat fluxes considers spanwise slices in z -direction, and due to the more demanding smoothing applied in this direction, the spanwise – y component of the laplacian is object of discussion. Figure 5 shows the results for the filtering techniques described earlier. The 4-times mean filter shows local edge effects and noise in proximity of the ribs. To mitigate these phenomena, the cubic smoothing spline is applied in direction y , the resulting map in figure 5 (b). The second derivative trend for the surface fitting method is monotonically increasing towards the edges in the central region, however the shape of the local interpolants in the other regions cause the second derivative to lose any symmetricity and therefore any physical significance. Finally, the second derivative of the cubic smoothing spline brings out the local features of the copper tracks, thus is not useful for the application under study.

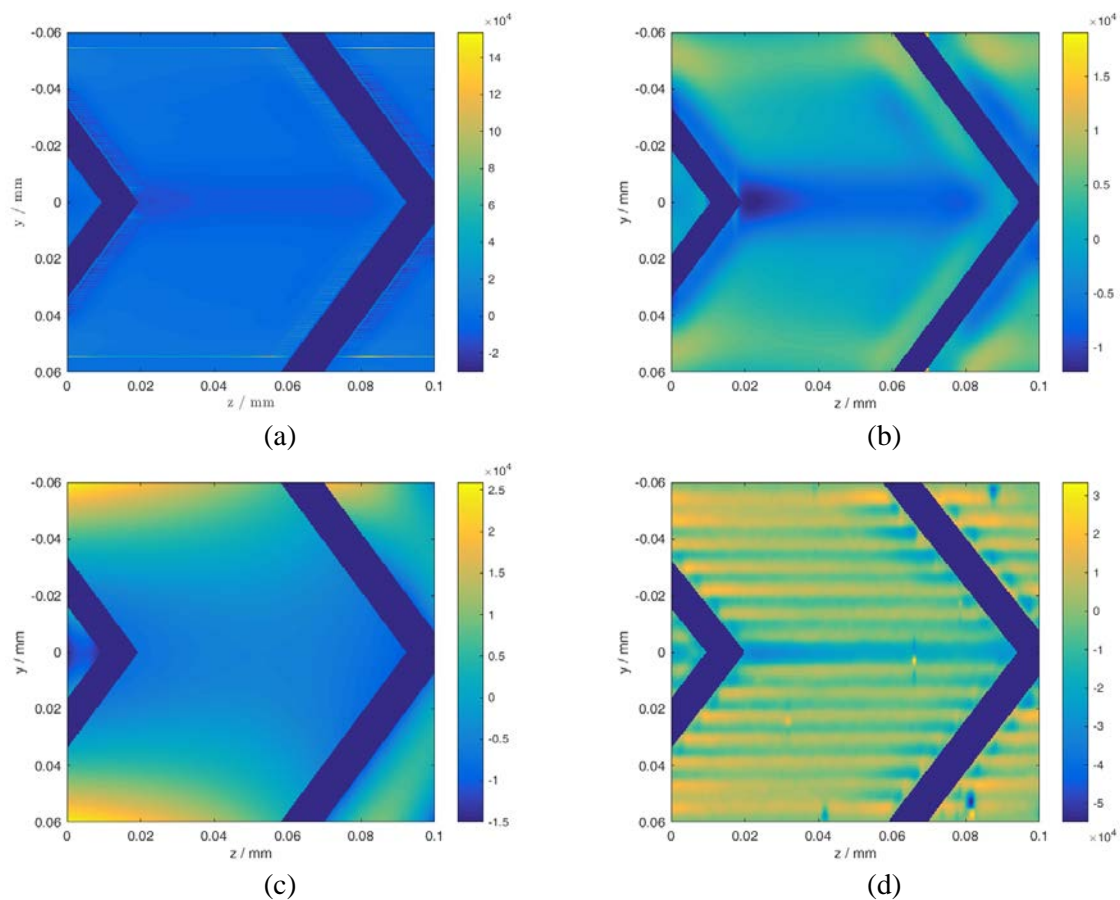


Figure 5. Second derivative in y -direction of the filtered thermograms with the following methods: mean filter 4x (a), mean filter 4x, then cubic smoothing of derivative (b), surface fitting (c) and cubic smoothing spline (d).

Finally, the effect of the three attempted smoothing schemes on the second derivative are shown in figure 6, for $z = 44$ mm. It is clear that the results are strongly dependent on the adopted filtering strategy, and the only feasible strategy for this application is the 4x mean filter, since the trend imposed by a fitting surface is too dependent on the choice of the equation of the curve.

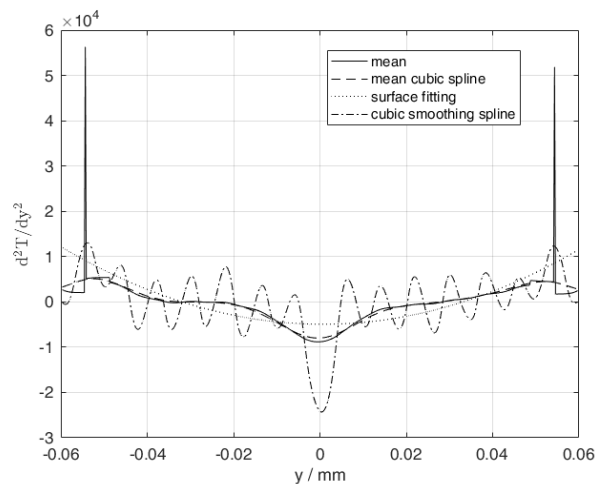


Figure 6. Second derivative in y-direction, $z = 44$ mm

4 Conclusions

The present study shows the effect of different image filtering techniques applied to the temperature field of the heating element in a closed channel for the analysis of local convective coefficient. Given the modelling necessity of eliminating from the temperature field the details of the copper tracks, because the assumption of a single equivalent conductivity is needed to avoid a complete FEM modelling of the copper tracks and their spacing, a few filtering strategies have been selected, to smooth the temperature field and to allow the calculation of the spatial second derivatives for the calculation of the laplacian term in the heat flux balance. It has been shown that the spanwise- cubic smoothing spline approach, with an appropriate choice of the smoothing parameter, gives a temperature field which is coherent with the unfiltered thermogram, i.e. without significant local temperature alterations. However, the calculation of the second derivatives shows that the latter method is unfit for this task, as the local variations due to the copper tracks are enhanced by the derivation process. The mean filter, when repeated four times, seems the most appropriate method to provide a derivable thermogram, however edge effects near the image borders and close to the rib regions make the second derivative useless without further smoothing. This information could also be used when using the same kind of heater in other experimental studies.

Following those considerations, further work will consist in evaluating the differences in term of heat flux with the described methods, while in terms of image processing techniques a higher order derivative scheme should be tried to verify the conclusions.

References

- [1] A Niro, D Fustinoni, F Vignati, P Gramazio and S Ciminà 2016 *J. Phys.: Conf. Series* **745** 032076
- [2] D Fustinoni, P Gramazio, L Vitali and A Niro 2017 *J. Phys.: Conf. Series* **796** 012015
- [3] P Gramazio, L Vitali, D Fustinoni and A Niro 2017 *J. Phys.: Conf. Series* **923** 012052
- [4] T Astarita, G M Carlomagno 2013 *Infrared thermography for Thermo-Fluid-Dynamics (Experimental Fluid Mechanics)* ed. Springer, chapp. 4-6
- [5] G Tanda 2004 *Int. J. of Heat and Mass Trans.* **47** 229–43
- [6] D Sarkar, A Jain, R J Goldstein and V Srinivasan 2016 *Int. J. of Therm. Sci.* **109** 413-23
- [7] A F M Torre, A Ianaro, S Discetti and G M Carlomagno 2018 *Int. J. of Heat and Mass Trans.* **127** 1138–46
- [8] S Rainieri and G Pagliarini 2002 *Exp. Therm. and Fluid Sci.* **26** 109–14
- [9] S Rainieri, F Bozzoli, G Pagliarini 2004 *Exp. Therm. and Fluid Sci.* **28** 179–83
- [10] O'Haver 2019 *Pragmatic introduction to signal processing*, University of Maryland, <http://bit.ly/1TucWLF>