Fachtagung "Experimentelle Strömungsmechanik"
7.–9. September 2021, Bremen

Simultane Temperatur- und Geschwindigkeitsmessungen in Wasserströmungen mittels MRV

Simultaneous temperature and velocity field measurements in water flows using MRV

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Volumetrische Temperaturmessungen, Magnet-Resonanz-Velocimetrie (MRV)
volumetric temperature measurements, magnetic resonance velocimetry (MRV)

Abstract

Temperature measurements in fluid flows using Magnetic Resonance Velocimetry (MRV) techniques can provide three-dimensional temperature fields in fluid flows, which can be used to study the heat transfer performance of convective systems such as heat exchangers. MRV does not require optical access and no temperature-sensitive seeding, which can be regarded as a major advantage compared to other temperature measurement techniques such as laser-induced fluorescence and thermochromic liquid crystals. Furthermore, MRV allows simultaneous full-field measurement of fluid velocities and fluid temperatures inside complex flow systems, which is not feasible with any other available measurement technique. Such experimental data sets are extremely useful to examine and design convective cooling systems, which are used, for example, in gas turbines, electrical engines, and electronic parts. As a conventional MRV method, the temperature changes in the fluid such as water are determined from the temperature sensitivity of the proton resonance frequency (PRF). This technique is known as PRF-shift and the relative temperature field is reconstructed from the phase-difference between two scans, one with target temperature field and one with reference temperature field. However, this technique is prone to several sources of error including the electrical conductivity of the used materials. In the present study, we develop and investigate a PRF-shift method that allows unbiased fluid temperature measurements in arbitrary heat exchanger geometries. All major errors are accounted for. The developed PRF-shift method is combined with MRV measurements of the fluid velocities providing a thorough understanding of the investigated system.

Introduction

MRV-based temperature measurements, known as Magnetic Resonance Thermometry, can provide three-dimensional temperature fields in water systems (Rieke & Butts Pauly 2008, Buchenberg et al., 2016). These measurements do not require optical access and no temperature-sensitive seeding since the signal carriers are the hydrogen protons in the water

molecules. In combination with velocity-sensitive MRV, full-field measurements of fluid velocities and fluid temperatures inside complex flow systems are possible.

In MRV, there are several techniques to acquire temperature fields. All these techniques have in common, that temperatures are indirectly measured via temperature-sensitivity magnetic properties of the fluid. For water systems, the choice of the MRV technique includes:

- Proton resonance frequency (PRF) shift:
  As the most commonly used technique in medicine, the temperatures in many fluids such as water can be determined from the temperature sensitivity of their resonance frequency. Since the frequency shift is relatively low, the temperature field is encoded in the phase angle of the signal (Φ). The acquired phase map also includes other effects, such as the background phase. A reference measurement is required to remove these effects and provide quantitative relative temperature fields (Rieke & Pauly 2008).

- Relaxation time correlation:
  The longitudinal (or spin-lattice) relaxation time T1 or the transverse (or spin-spin) relaxation time T2 can be used to measure absolute temperature fields in fluid flows without a reference acquisition (Leclerc & Métivier 2018). However, the correlations between T1 or T2 and the fluid temperature must be determined in a calibration scan.

Depending on the technique, either a reference acquisition or a calibration scan is required additionally to the temperature field acquisition. In this study, the PRF-shift method is chosen. The reason is that this method can utilize a basic Gradient Recalled Echo (GRE) sequence, and that a reference scan without heat transfer is simply conducted.

The temperature sensitivity in a GRE scan depends on the PRF change coefficient (α), which describes the proportionality rate of proton resonance frequency on temperature, the gyromagnetic ratio (γ), the main field strength (B_0) and the time duration available for phase evolution (τ). The same pulse sequence is played out twice, once with the target temperature field (subscript: TEMP), and once with isothermal condition as reference (subscript: REF), resulting in the relative temperature field:

$$\Delta T = T_{TEMP} - T_{REF} = \frac{\Phi_{TEMP} - \Phi_{REF}}{2\pi\, \alpha\, \gamma\, B_0\, \tau} \qquad (1)$$

The static background phase, that is caused by B_0-inhomogeneity, and errors related to the magnetic gradient system cancels out in the phase difference of the two acquisitions. For a standard GRE pulse sequence used in many PRF-shift studies, the parameter τ equals the echo time (TE).

Under ideal conditions, Eq. (1) would provide a quantitative map of the temperature differences between the two scans. However, in real measurements, a number of effects need to be considered.

- Magnetic field drift
  Time-dependent changes of the background magnetic field can occur for example due to intensive gradient use that heat up components of the MRI system. As an approximation, these changes are homogenous in space. The phase drift can be estimated from a time series of measurements or from reference region of interest (ROI) in which temperatures are assumed constant over time.
- Susceptibility-related effects
  The susceptibility of materials generally varies with temperature. As a result, the magnetic field changes between the temperature acquisition and the reference

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acquisition which occurs as errors in the temperature results. Since the susceptibility-induced phase change and the PRF shift depend both on temperature, it is difficult to differentiate between the two effects. A remedy is to use only materials that have a magnetic susceptibility with a low temperature sensitivity.

- Conductivity-related effects
  Another effect particularly important to the study are the eddy currents that are induced in the metal parts of the heat exchanger model. Electrical conductivity typically depends on temperature. As a result, this effect does not cancel out in the phase differences between the temperature scan and the reference scan in Eq. (1).

Methods

Starting with a basic GRE sequence, a method is developed step by step to reduce the major errors that can occur in PRF-shift MRV acquisitions. The working fluid is assumed to be a water solution with known PRF change coefficient. Furthermore, it is assumed that some parts of the heat exchanger system are made of electrically conductive material. Note that most materials suitable for technical heat exchangers, are metals and therefore, electrical conductivity is a relevant source of error.

Conductivity-related phase changes and the correction of this spurious effect is one of the most crucial tasks in this study. The magnitude of these effect depends on the Faraday's law of induction, and is therefore proportional to the electrical conductivity of the material. The main source of induction is the switching of the magnetic field gradients that are used for spatial encoding (Graf et al., 2005).

In principle, all spurious phase changes that are related to a specific gradient must change their sign if the gradient is played out with reverse polarity. It is assumed that except for the sign change, all effects are identical. A practical solution to reverse the polarity of all gradients is to flip the image orientation on all encoding axes. The eddy-current corrected temperature map can be calculated from the sum of two acquisitions (Bruschewski et al., 2020):

$$T = \frac{\Phi_{0°} + \Phi_{180°}}{2\pi\, \alpha\, \gamma\, B_0\, (2\, TE)} \tag{2}$$

The subscripts 0° and 180° denote the orientation of the encoding axes. i.e. the polarity of the gradients. Note that the temperature sensitivity is increased by factor 2, i.e $\tau = 2\, TE$, because the PRF shift of the two acquisitions add up. With Eq. (1), the relative temperature field becomes:

$$\Delta T = \frac{\Phi_{0°,TEMP} + \Phi_{180°,TEMP} - (\Phi_{0°,REF} + \Phi_{180°,REF})}{2\pi\, \alpha\, \gamma\, B_0\, (2\, TE)} \tag{3}$$

Results

Using the method in Eq. (3), imaging errors related to the electrical conductivity of the flow system can be reduced to a minimum and MRV-based temperature field measurements are made possible in heat exchanger systems partly made of metal. Besides, all other major sources of errors can be compensated after the scan, which is explained in Bruschewski et al. (2020).

Figure 1 shows unbiased measurement results of the fluid velocities and fluid temperatures in a pin fin heat exchanger setup. Figure 2 illustrates how this method can be used to analyze the transient heat transfer in a periodic film cooling experiment.

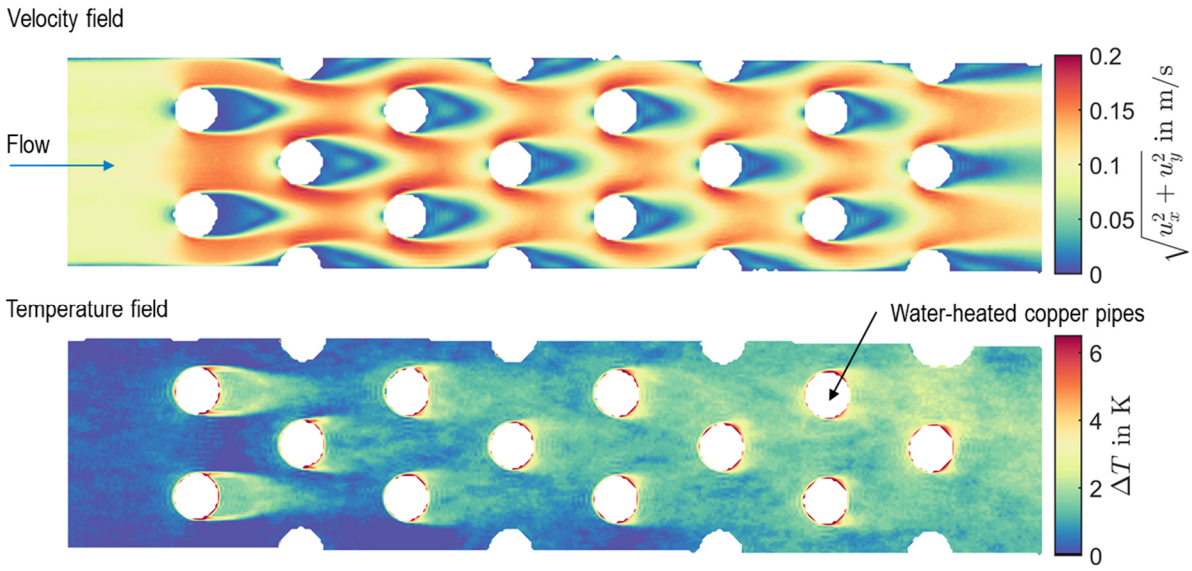

Fig. 1: Stationary MRV-measurements of the fluid velocities and relative fluid temperature in a pin fin array comprised of a water flow through heated copper pipes (Bruschewski et al., 2020).

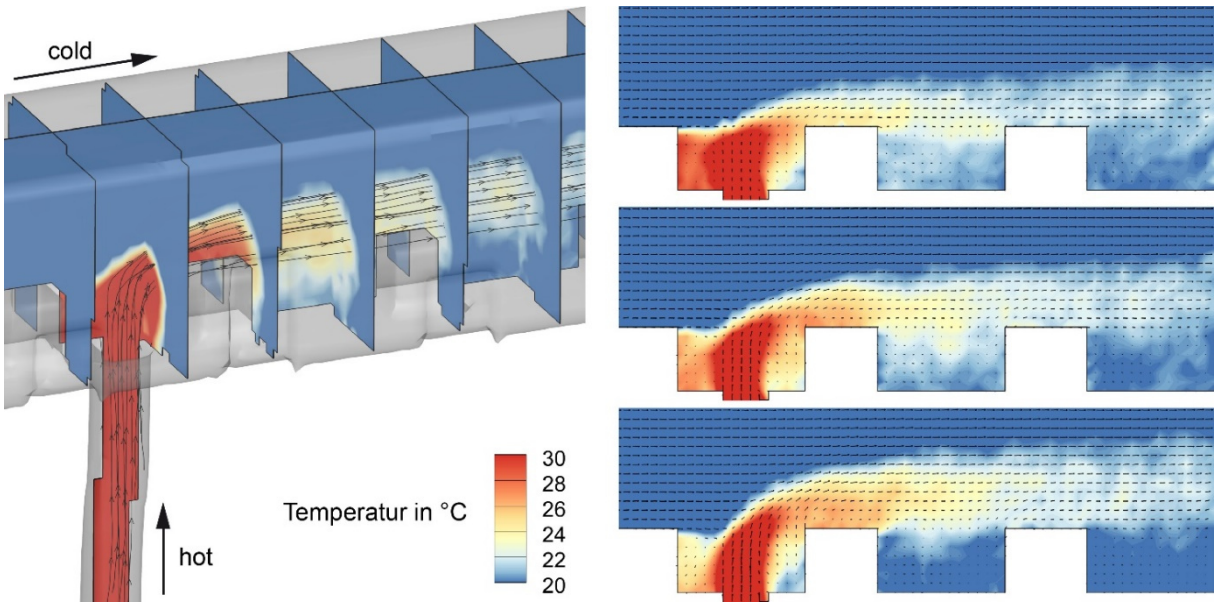

Fig. 2: Phase-locked MRV-measurements of the fluid velocities and absolute fluid temperatures in a film-cooling experiment with a pulsatile injection (cycle time: 1.5 s, time step size: 0.075 s). Three representative time steps are shown right.

Discussion & Conclusion

The purpose of this study was to develop a new MRV technique to study the temperature fields in fluid flows. Particular focus was on the formation of measurement errors that can occur if the investigated system contains metal parts. Metals seem inevitably for many heat transfer experiments because no commonly available non-metallic material reaches the same level of thermal conductivity as for example, copper. Without the possibility to use metal parts, MRV experiments may not reach the target heat transfer characteristics.

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The developed method allows unbiased temperature field measurements in arbitrary flow systems using water as the flow medium. Such experimental data sets are extremely useful to examine and design convective cooling systems, which are used, for example, in gas turbines, electrical engines, and electronic parts. The MRV technique does not require optical access and no temperature-sensitive seeding, which can be regarded as a major advantage compared to other temperature measurement techniques.

Literature

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