MR thermometry in in-vitro flows

Waltraud B. Buchenberg[1], Florian Wassermann[2], Sven Grundmann[2], Bernd Jung[3], and Robin Simpson[1]

[1]*Dept. of Radiology, Medical Physics, University Medical Center Freiburg, Freiburg, Germany,* [2]*Center of Smart Interfaces, Technische Universität Darmstadt, Darmstadt, Germany,* [3]*Institute of Diagnostic, Interventional and Pediatric Radiology, University Hospital, Bern, Switzerland*

Purpose: Since MR thermometry (MRT) is a non-invasive method to monitor temperature it is commonly applied in the medical field for MR safety studies and MR-guided interventions. MRT based on proton resonance frequency (PRF) shift allows a quantitative monitoring of the change in temperature, ΔT [1].

Temperature distributions in technical flows are of great interest to the engineering community, to investigate heat transfer for performance improvement of devices or case studies to compare with numerical simulations. Gathering 3D temperature fields is currently not feasible since the presence of conventional temperature probes in flowing liquid alters the flow profile and thus the local temperature distribution. Promising preliminary results of MRT applied to a turbulent pipe flow with constant temperature were reported by Elkins et al. [2] however the capability of MRT to comprehensively measure temperature distributions in technical flows has not yet been widely investigated.

This work aimed to investigate the temperature distributions in a countercurrent doublepipe heat exchanger consisting of two separate closed flow circuits. The heat was transferred from the inner, hot, flow circuit (flow 2) to the surrounding, non-heated, flow circuit (flow 1). An MR compatible flow model was established to acquire 3D TMs with flow 1=5l/min, and 10l/min.

Methods: A schematic diagram of the entire setup can be seen in Figure 1. Two flow circuits passed from the console room (grey dotted outline) to the scanner room (red dotted outline). The flow 1 circuit (black lines) consisted of a reservoir of distilled water with 1% $CuSO_4$ solution (blue box) connected to a pump and flow control system (green box), which provided variable flow rates (5l/min or 10l/min). An immersion cooler (Julabo FT402, Seelbach, Germany) was used to maintain a constant temperature. The flow 2 circuit (orange lines) consisted of a smaller reservoir of distilled water (no CuSO4 was used as signal was not received from this circuit, see below) connected to a circulation heater/cooler (Julabo FC1200T and Julabo SE, class III, Seelbach, Germany) providing fluid temperatures of either 21°C or 50°C and a constant flow rate of 24l/min.

The flow model consisted of a copper pipe (outer diameter=15 mm) inside a Plexiglass® pipe (inner diameter=50mm, length of both pipes=320mm) oriented parallel to the magnetic field (for reference a cross sectional view of results in the flow model can be seen in Figure 2a or 2b). The flow 1 circuit was connected to the outer pipe, while the flow 2 circuit was connected to the inner pipe. The aim of the experiment was to measure the resulting heat distribution in flow 1 when the temperature of flow 2 was increased. Copper was used for the inner pipe due to its high thermal conductivity, it has a similar susceptibility to that of water [3] and it acts as a Faraday cage such that no MR signal is received from flow 2, preventing flow artefacts.

MR proton resonance frequency (PRF) shift thermometry was performed on the flow model using a 3T system (Prisma, Siemens, Germany) and a velocity compensated GE FLASH sequence. 3D imaging volumes were acquired with TR/TE=24.9/16ms, flip angle=7°, pixel bandwidth=120Hz/pixel, spatial resolution=1.2mm isotropic, PE lines=96, slices=120. Reference phantoms (5% Hydroxyethylcellulose+1%$CuSO_4$+dist. H_2O) surrounded the flow model to allow correction for field drift and Eddy currents. The imaging was performed twice: firstly, with both flow circuits at room temperature (heat off) and secondly with flow 1=room temperature and flow 2=50°C (heat on). The resulting phase images were subtracted and converted to temperature increase using $\Delta T = \dfrac{\Delta\Phi}{2\pi \cdot f \cdot \alpha \cdot TE}$ (f: imaging frequency, $\alpha_{1\%\ CuSO4}$=0.0097 ppm/K, TE=16ms). Local reference temperatures within the Plexiglass® pipe were acquired with fiber optical probes (FOP, FOTEMP 4, probe TS2, Optocon AG, Dresden, Germany). The presence of probes in the imaging FOV disturbs the measurements and so the actual inlets of the probes were about 2cm upstream with respect to the first slice used for calculating Figure 2.

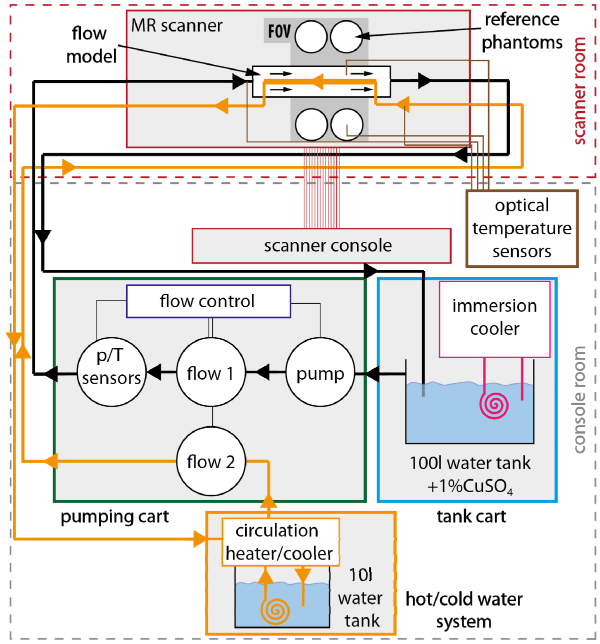

Fig.1: Measurement setup.

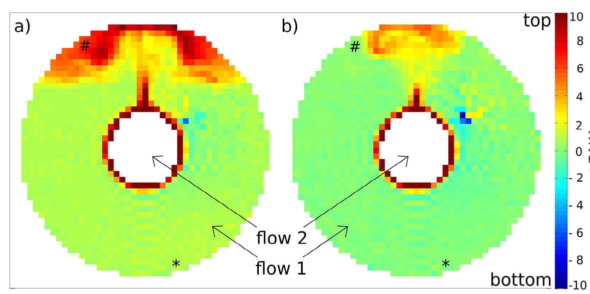

Fig.2: Cross-sectional TMs: flow 1 (into the page)=5l/min (a) and 10l/min (b). Measured temperature changes in flow 1 are localised to a thin region directly above flow 2, and a larger region at the top of the Plexiglass® pipe, the shape and extent of which depends on the flow rate. Due to the copper pipe, flow 2 is not MR visible.

Results: Figure 2 shows TMs of a cross-sectional view averaged over 10 slices (the heat distribution is assumed constant over this distance). Clearly visible is a temperature increase at the upper part of the outer pipe for both flow rates; however, the spatial temperature distribution depends strongly on the flow rate. Lower temperatures are seen if the flow rate is doubled as the induced heat is carried away more efficiently. In the major part of the cross section no temperature increase occurs. The temperature increase measured by the FOP at two locations (approximate position within the slice depicted by # and * in Fig.2) was 6.5K (#) and -0.2K (*) for flow 1=5l/min and 0.3K (#) and -0.1K (*) for flow 1=10l/min. Average values from a 4-voxel ROI at these locations give MR measured ΔTs of 6.4K (#) and 0.9K (*) for flow 1=5l/min and 0.2K (#) and 0.0K (*) for flow 1=10l/min. The TMs shown here were reproducible in additional measurements at this MR system and also at 1.5T (not shown).

Discussion: The temperature distribution in a heat exchanger has been successfully measured using MRT. Since the FOP inlets disturbed the TMs locally, a stack of slices at a sufficient distance was chosen for the data evaluation. Precise quantitative comparisons between FOP and MR measurements are therefore difficult, however our preliminary results agree well with the temperature increase measured by FOPs. A velocity compensated sequence was applied to account for fluid velocity effects and higher order effects such as acceleration are assumed to be small in this particular setup and thus neglected. However, these effects could bias TM results in more complex geometries and flows [2]. Additional measurements are required to quantitatively analyze the accuracy of the TMs and verify them, for example by measuring ΔT at various other locations with FOPs. Furthermore, temperature maps obtained by numerical simulations will be compared to the presented results in a future step. In addition, since the hot water causes the formation of air bubbles at the surface of the copper tube over time, cold water (~5°C) will be used instead to cool the outer fluid in future experiments.

MRT is a very promising technique to be applied to thermo-fluidic disciplines to help understanding devices such as heat exchangers. Challenges and requirements of MRT in medicine might differ at several parameters compared to the ones in engineering setups. However, the medical field could also benefit from collaborations with engineering researchers; for example, the design of MR compatible setups for engineering problems is challenging and, thus, will require the investigation of a variety of materials which could help to develop MR compatible medical devices.

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References: [1] Rieke & Pauly JMRI 2008;27:376-390 [2] Elkins *et al.* Heat&Fluid Flow 2004;25:702-710 [3] Schenck Med Phys 2006;23(6):815-850