Multiphysics Modeling and Prototyping of a Wearable Sensor for Sweat Rate Measurements

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SenseRisc Project

Sviluppo di abiti intelligenenti sensorizzati per prevenzione e mitigazione di rischi per la sicurezza dei lavoratori.
Agenda

- Motivation: why sweat rate sensing
- Device design
- Research questions
- Multiphysics model setup
- Prototype
- First results for vapor flow
- Outlook
Motivation: why sweat rate measurements?

- Intuitively, sweat secretion signals physical and thermal stress.
- It can help to evaluate:
  - loss of body water by transpiration
  - fatigue or overheating.

Sweat rate measurements can be conducted with non-invasive sensing devices (e.g. wearable sensors).

Nevertheless...

Sweat rate depends on:
- Skin conditions, physical activity.
- Environmental conditions.

Device design

Sense-RISC motivation:

The development of wearables with sensing capabilities to prevent and mitigate risk for workers.

Sweat rate sensor insights:

• Portable device, able to produce continuous and real-time measurements.
• Washable, simple to strap on.
• Prototype produced and tested.

Model for multiphysics assessment

Project approach: the open chamber

- Vapor diffuses along the chamber.
- Flux estimation through differential measurement.
- Enable continuous operation.
- Susceptible to disturbance by surrounding air.


Moisture transport by diffusion

Model for water vapor pressure vs. temperature (Antoine’s equation).

Mass diffusion follows the first Fick’s law:

$$\vec{j}_i = -\rho D_i \nabla m_i$$

Assuming one-dimension dimension and ideal gas:

$$j_{vapor} = \frac{D_{vapor} M_{H2O}}{RT} \left( \frac{\Delta P}{\Delta z} \right)$$

where:

$$\Delta P = r_h_1 P_{sat,T_1} - r_h_0 P_{sat,T_0}$$

that can be estimated from relative humidity (r.h.) and temperature readings along the diffusion path.
Research questions

How do the external conditions (air velocity, temperature) affect the vapor transport inside the chamber?

- Delimitation of possible conditions on expected user cases.
- Observation of relative and absolute humidity along inside the chamber.

How does the actual vapor distribution affect the sensing operation?

- Placement of humidity/temperature sensors along the open chamber.
- Selection humidity/temperature sensors based on sensitivity.
Multiphysics model in COMSOL

Turbulent flow:
- Air stream inlet
- Velocity profile
- Air stream outlet
- Walls

Moisture transport
- Moist surface: skin
- Moist air inflow
- Insulation

Heat transport
- Skin temperature
- Ambient temperature
- Latent heat sink
- Device insulated

Initial conditions:
- $T_{\text{amb}} = 25^\circ C$
- Rel. hum. $\phi_0 = 70\%$

Skin surface $T_{\text{skin}} = 33^\circ C$

Angle $\alpha$

Air boundary inlet

Air boundary outlet

Air stream

Open chamber fixture
Model simulation setup

Stationary study

• First study to conduct, only on Turbulent Flow physics.
• Wall Distance Initialization step (finer mesh at the wall required, Low Re wall treatment).
• Run for 0.01, 0.1, 1, 3 and 5 m/s, with angles of 0°, -30° and -60°.
• Results: steady-state air flow velocity and pressure distribution.

Time Dependent study

• Takes the stationary study results as steady-state input.
• Conducted on Moisture and Heat transport physics.
• Run until t = 20 seconds.
• Initial step 0.001 s, max. step 0.05 s.
• Results: time-dependent moisture and temperature distribution.
Results: air velocity and temperature

**Velocity**

Air flow inlet at 1 m/s, angle of -60°.

**Temperature**

Detail of temperature distribution for the previous air flow.
Results on evaluation axis (wind angle -60°)

Height 17 mm, diameter 7 mm

- Relative humidity trend is disturbed around the chamber height and more pronounced at higher air speeds.
Potential impact on design

Example: Relative humidity distribution, 4 mm Ø. Air flow inlet at 1 m/s, angle of -60°.

![Graph showing relative humidity distribution](Image)

**Δ r.h.:** moisture sensor

**Δ Z:** vertical distance above the skin [mm]

**Δ ε:** sensor uncertainty

**Design Trade-offs:**
- Moisture sensors should be allocated, so that Δ r.h. is larger than the sum of Δ ε of each sensor.
- For given a Δ ε and Δ Z, Δ r.h measurement can only be discerned below particular limit conditions (air speed, angle).
Prototype

- Multi-sensor system supported on a 3D printed structure.
- Battery powered, data transmission via Bluetooth.
- Android app for real-time monitoring and data logging.
Prototype: first results for vapor flow

- Two drops of water (1 µL each) dispensed in a calibration cap under the open chamber.
- Calibration actual vs. reference depending on setup and yet to be completed.
Outlook

• Multiphysics modeling shows how, due to the effect of surrounding air flows, the humidity profile diverts from the simple 1-D diffusive transport.

• The identification of the moisture distribution can help to place the moisture and temperature sensors in an optimal location.

• Next experiments using controlled air flows will help to evaluate the impact of air velocity on the sweat rate calculation model.

Limitations:
• Simulation model is limited to boundary conditions and 2-D geometry.
• Prototype calibration depends on an experiment setup, yet to be completed, which must reproduce real-like conditions and typical user cases.
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