TEST 1

PEX-A1

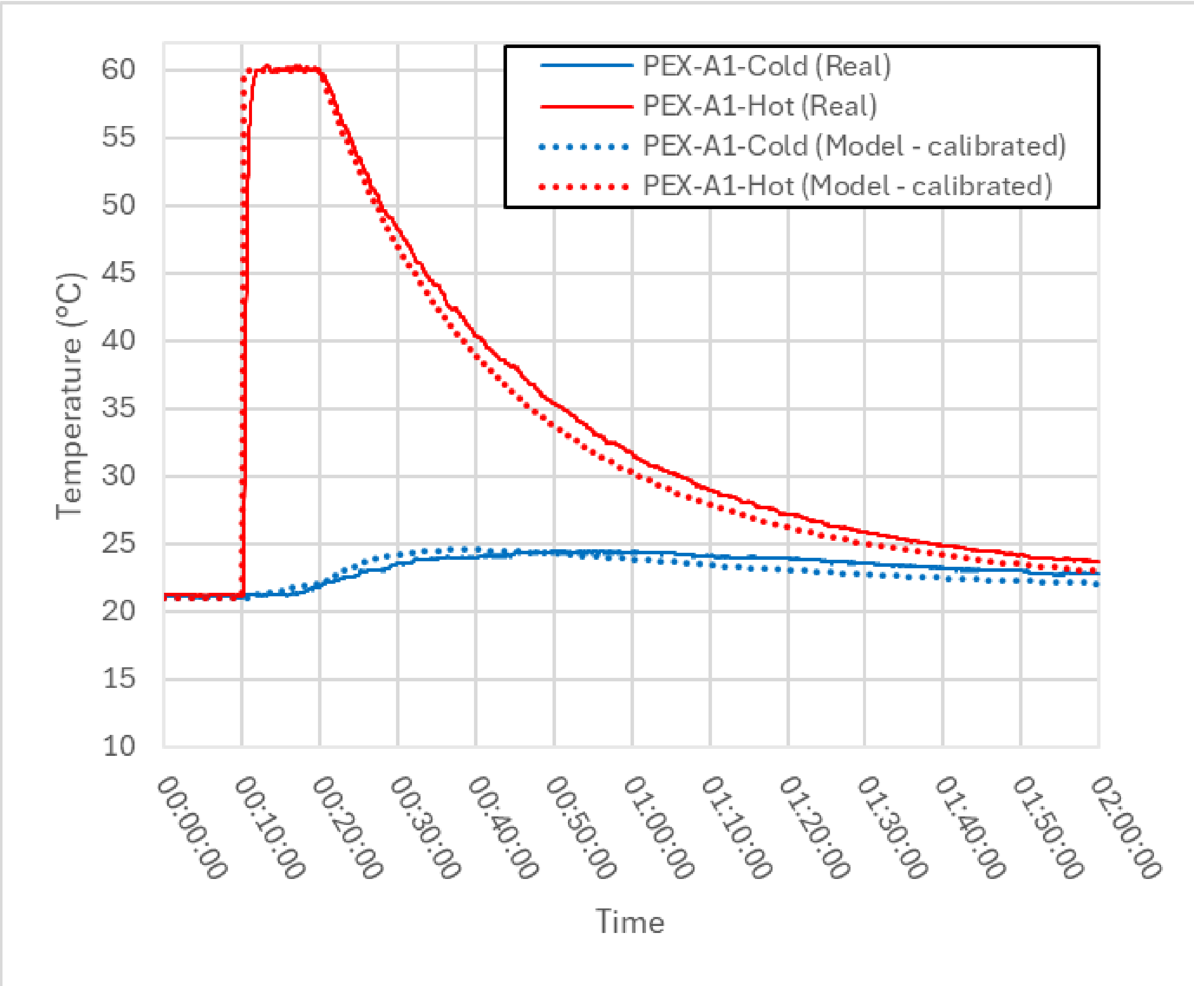


Figure S1. Shower PEX-A1. Temperature vs Time measured, modelled with radial and axial conduction and convection (calibrated for pipe PEX-A1-Cold)

PEX-B1

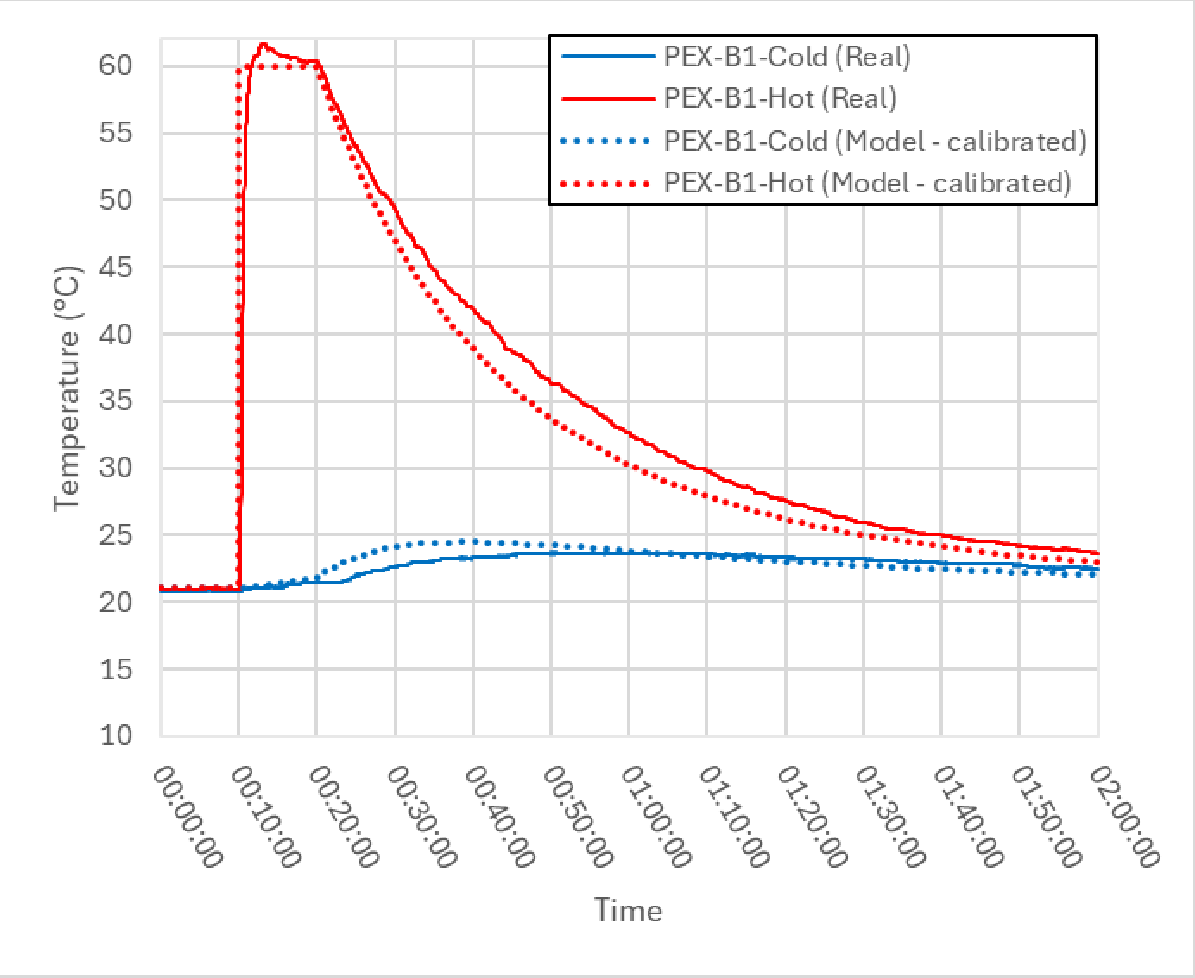


Figure S2. Shower PEX-B1. Temperature vs Time measured, modelled with radial and axial conduction and convection (calibrated for pipe PEX-A1-Cold)

PEX-C1

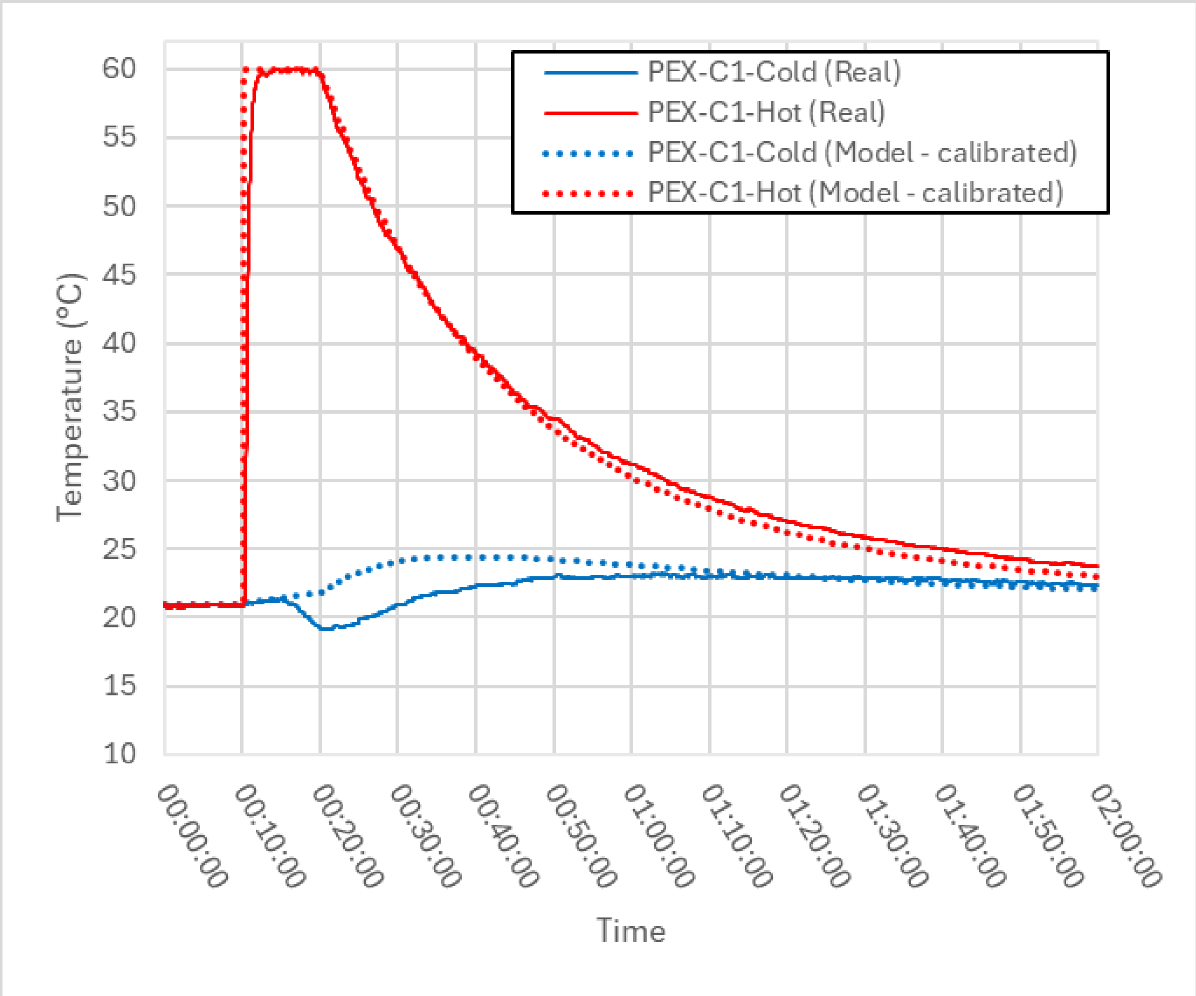


Figure S3. Shower PEX-C1. Temperature vs Time measured, modelled with radial and axial conduction and convection (calibrated for pipe PEX-A1-Cold)

Cu-A1

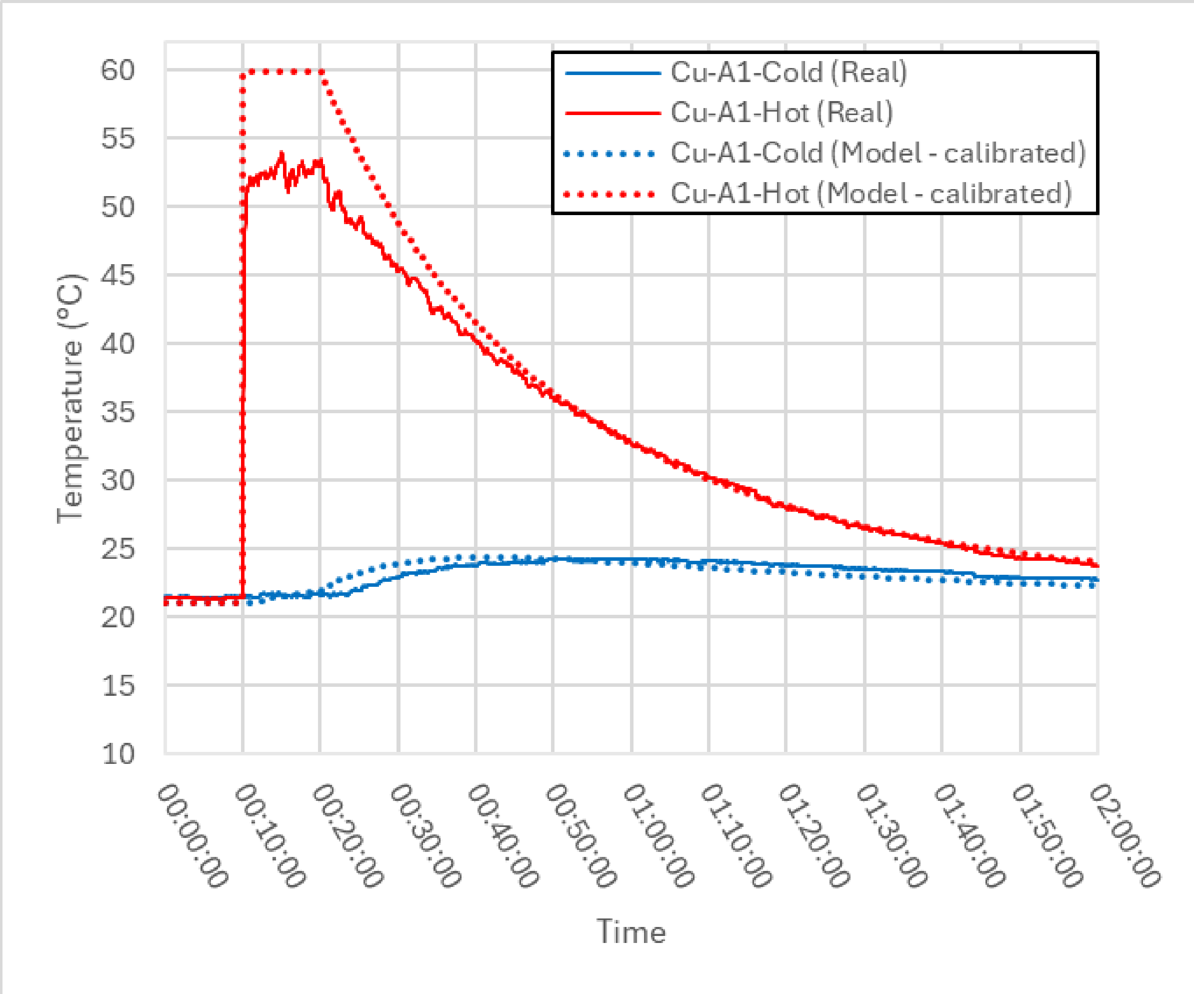


Figure S4. Shower Cu-A1. Temperature vs Time measured, modelled with radial and axial conduction and convection (calibrated for pipe PEX-A1-Cold)

Cu-B1

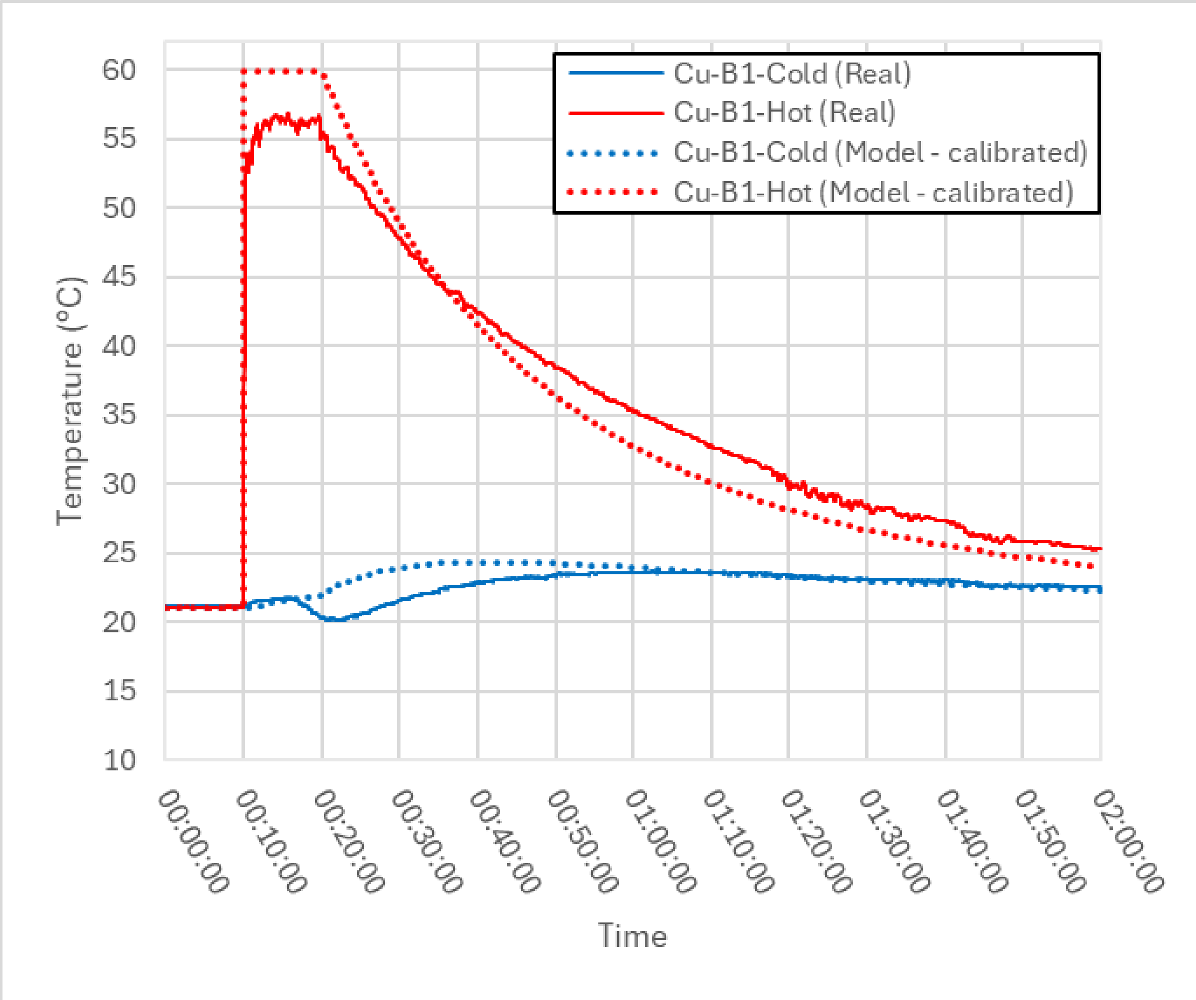


Figure S5. Shower Cu-B1. Temperature vs Time measured, modelled with radial and axial conduction and convection (calibrated for pipe PEX-A1-Cold)

Cu-C1

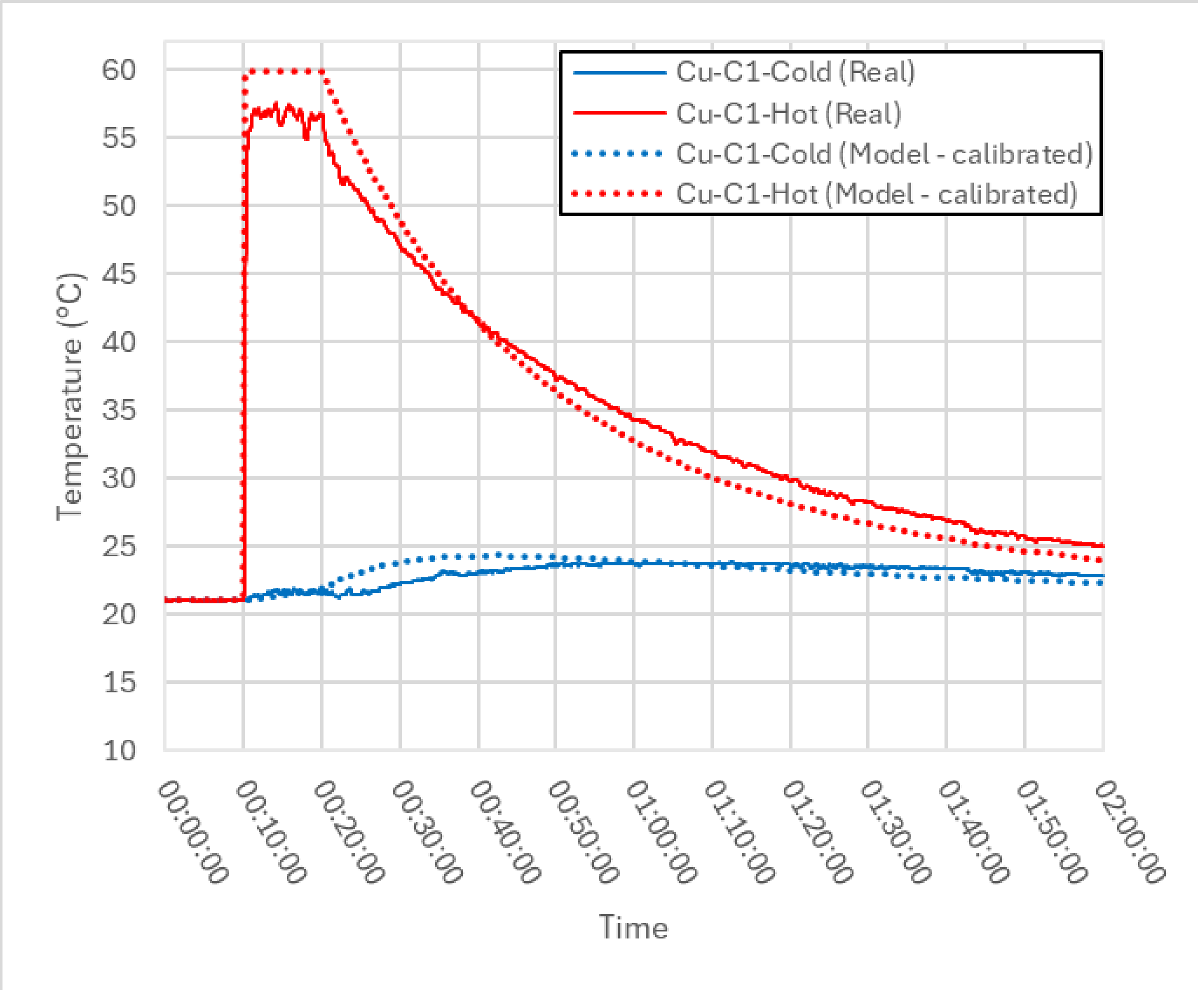


Figure S6. Shower Cu-C1. Temperature vs Time measured, modelled with radial and axial conduction and convection (calibrated for pipe PEX-A1-Cold)

TEST 2

PEX-A2

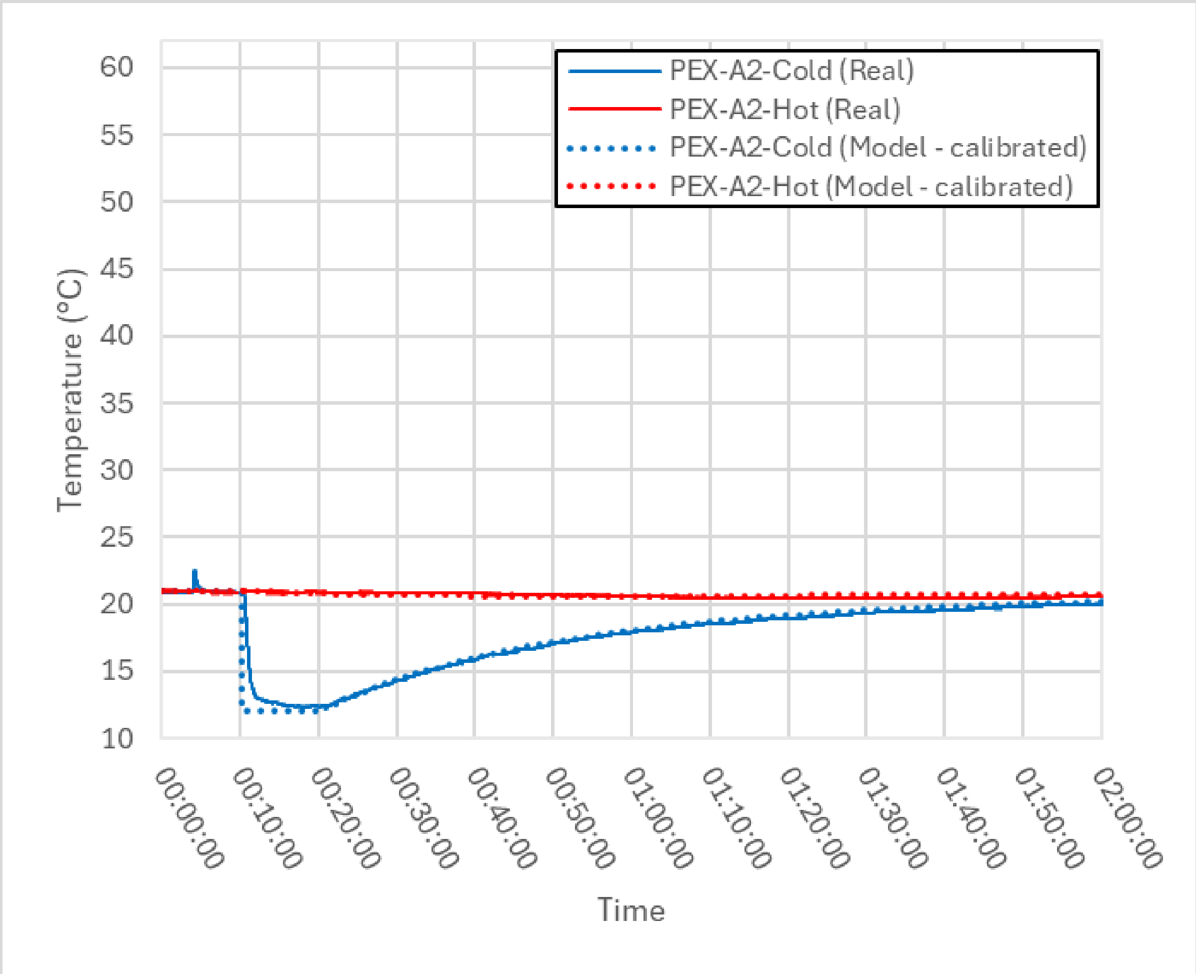


Figure S7. Shower PEX-A2. Temperature vs Time measured, modelled with radial and axial conduction and convection (calibrated for pipe PEX-A1-Cold)

PEX-B2

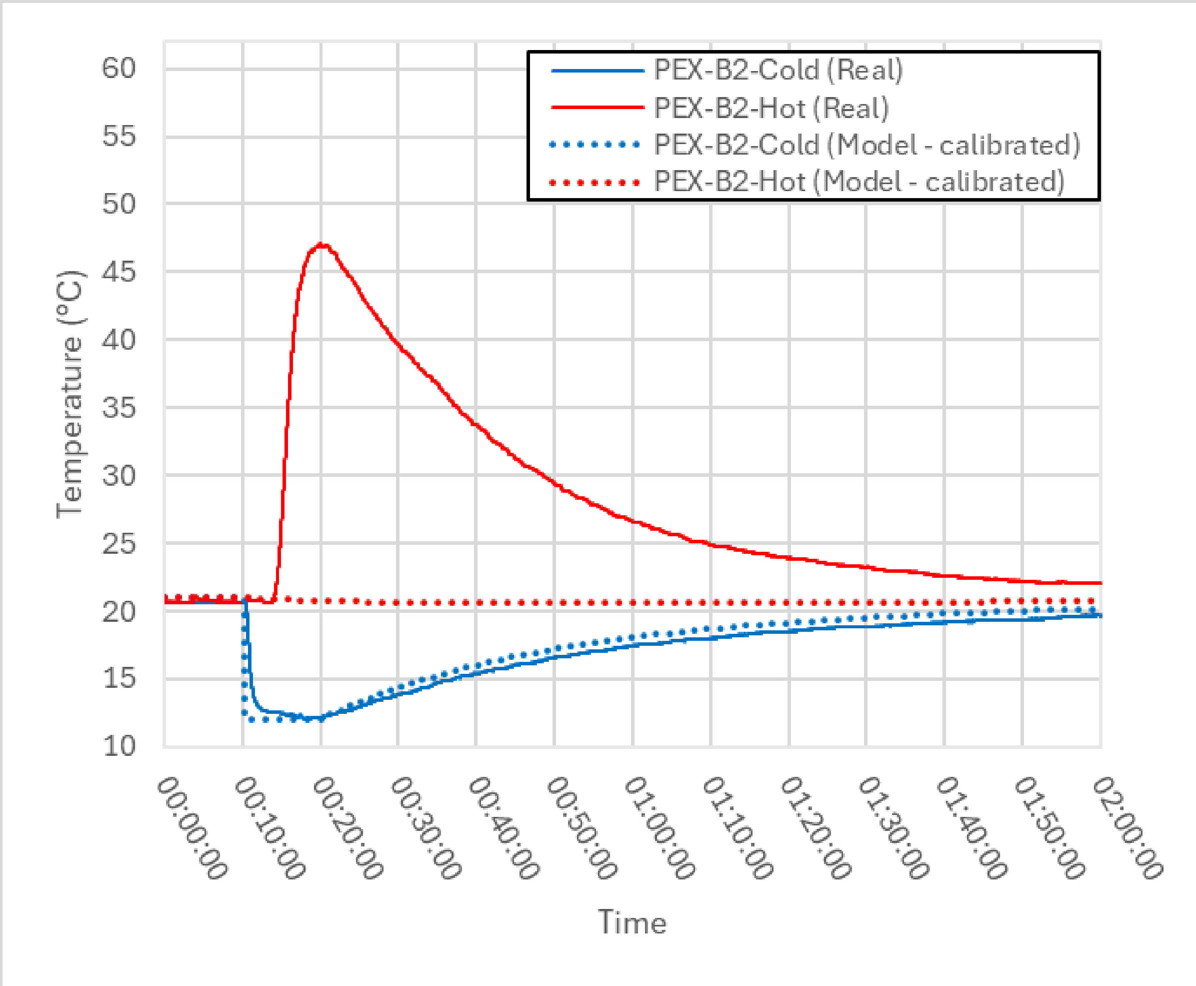


Figure S8. Shower PEX-B2. Temperature vs Time measured, modelled with radial and axial conduction and convection (calibrated for pipe PEX-A1-Cold)

PEX-C2

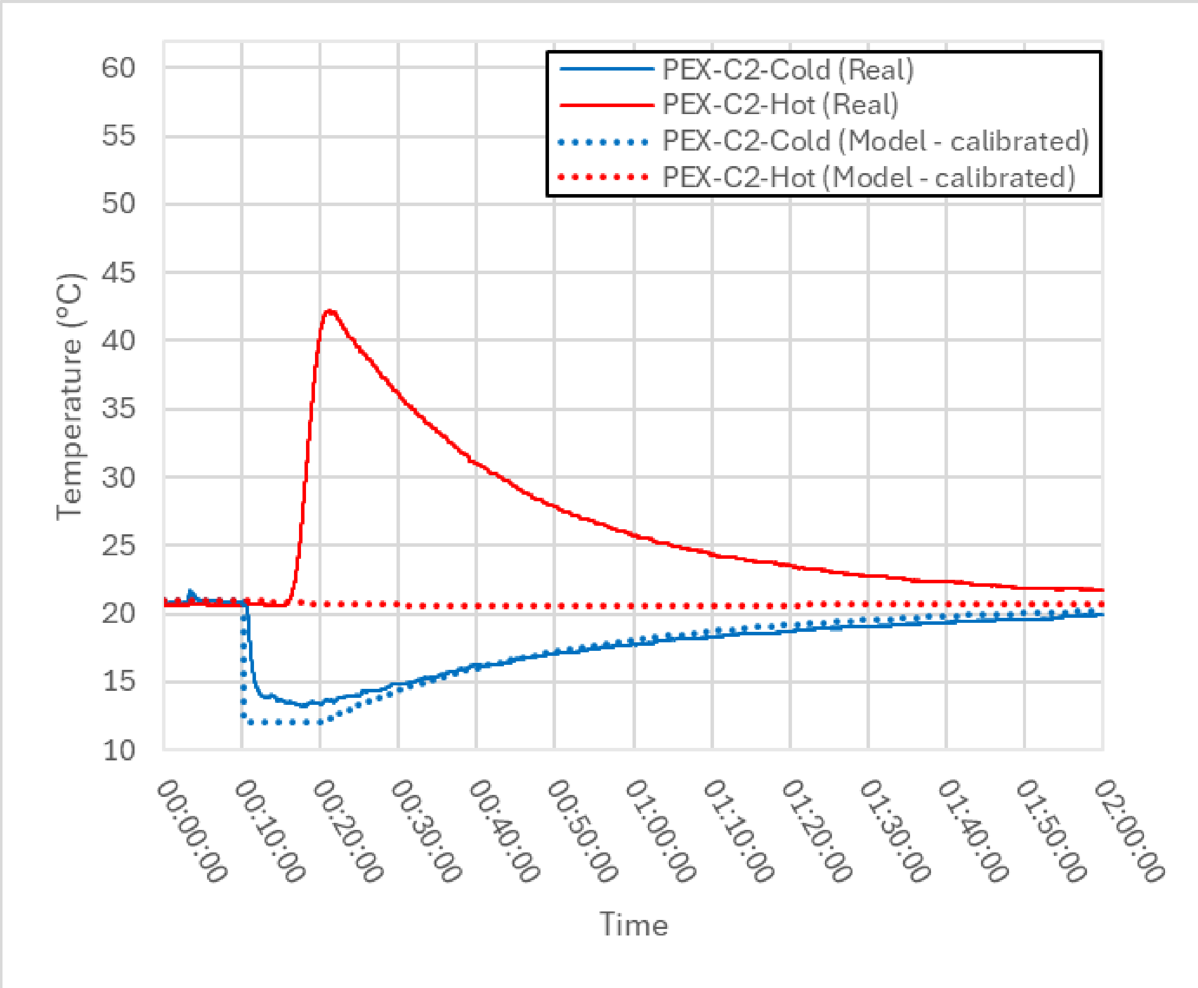


Figure S9. Shower PEX-C2. Temperature vs Time measured, modelled with radial and axial conduction and convection (calibrated for pipe PEX-A1-Cold)

Cu-A2

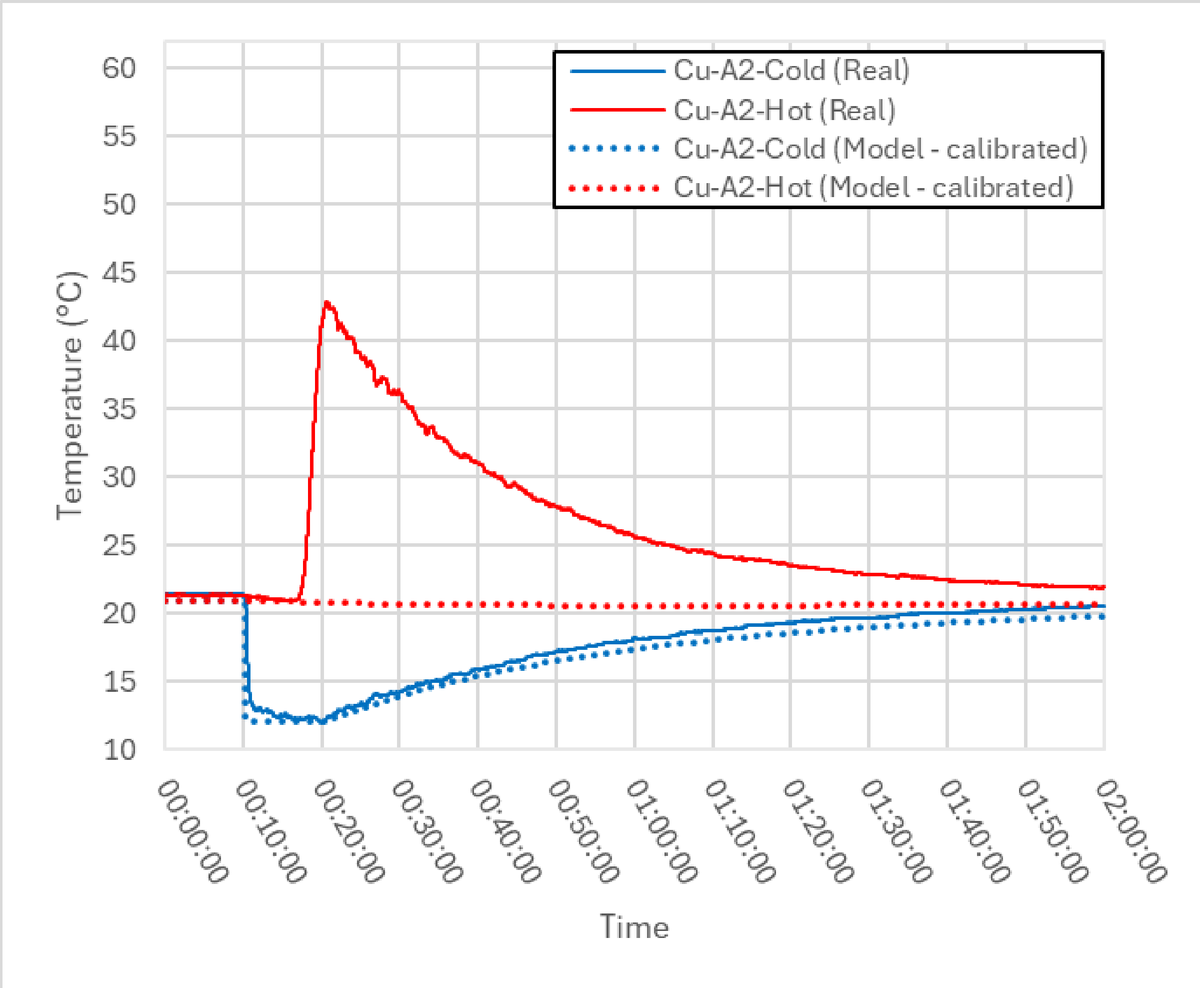


Figure S10. Shower Cu-A2. Temperature vs Time measured, modelled with radial and axial conduction and convection (calibrated for pipe PEX-A1-Cold)

Cu-B2

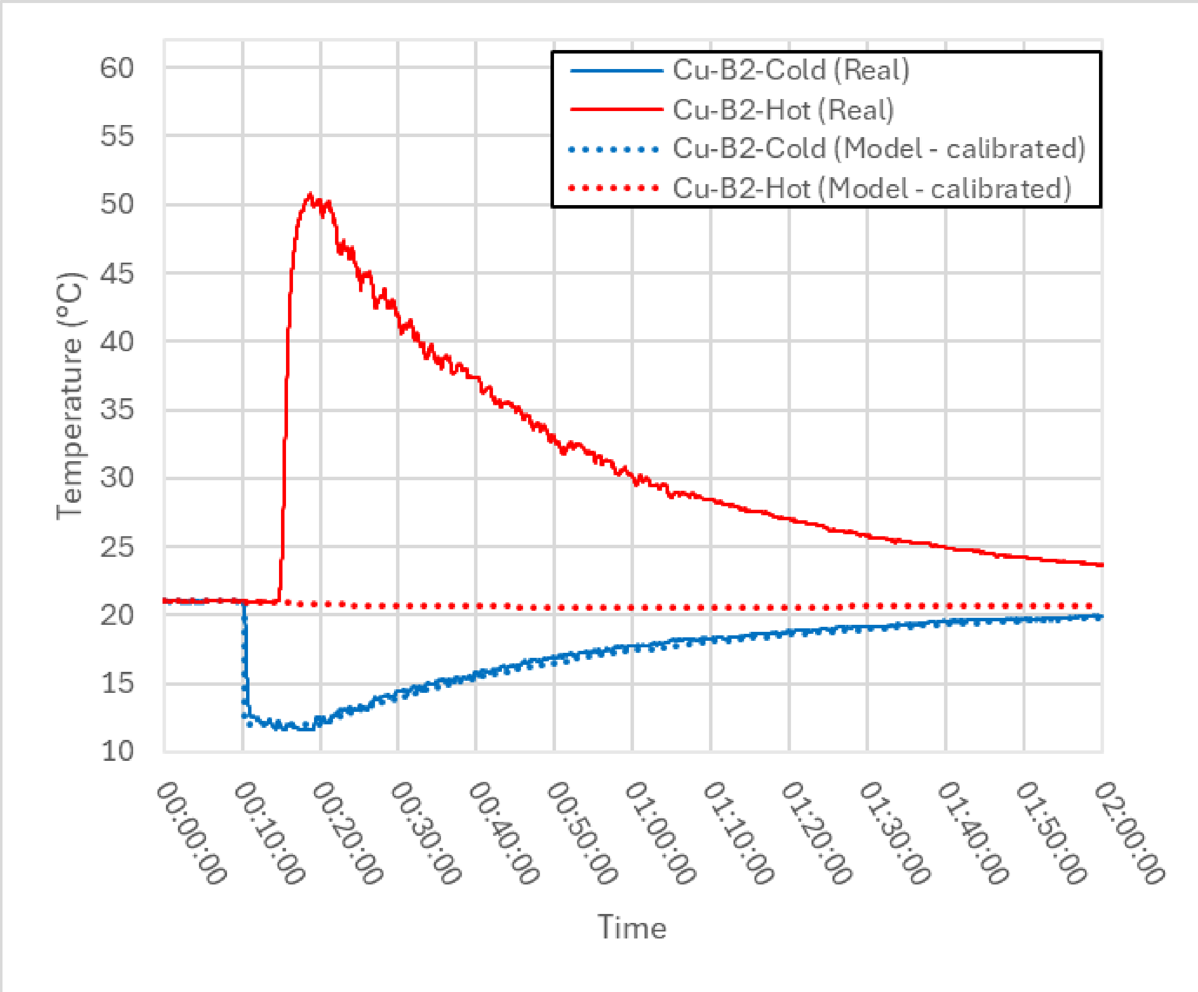


Figure S11. Shower Cu-B2. Temperature vs Time measured, modelled with radial and axial conduction and convection (calibrated for pipe PEX-A1-Cold)

Cu-C2

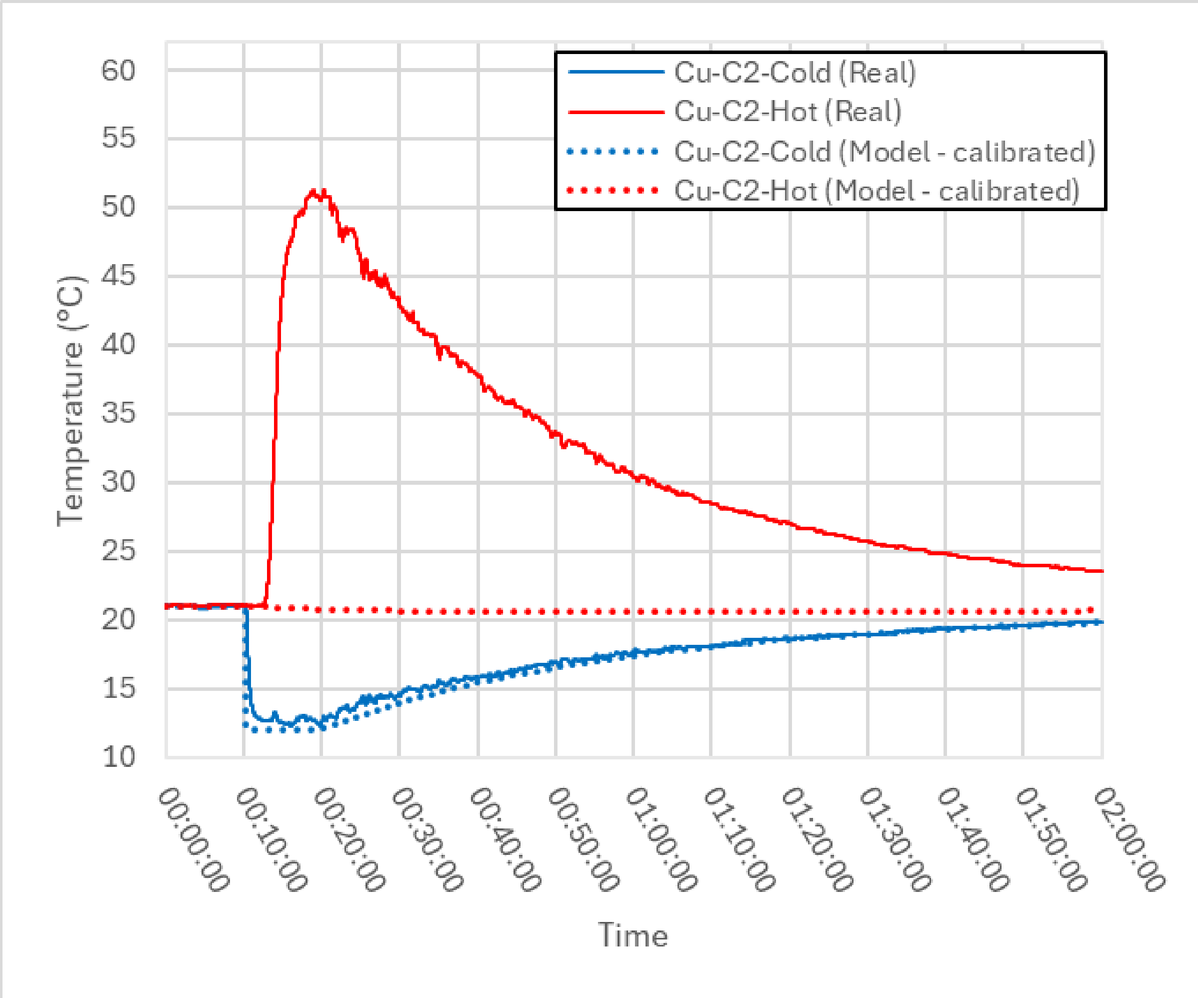


Figure S12. Shower Cu-C2. Temperature vs Time measured, modelled with radial and axial conduction and convection (calibrated for pipe PEX-A1-Cold)

TEST 3

PEX-A3

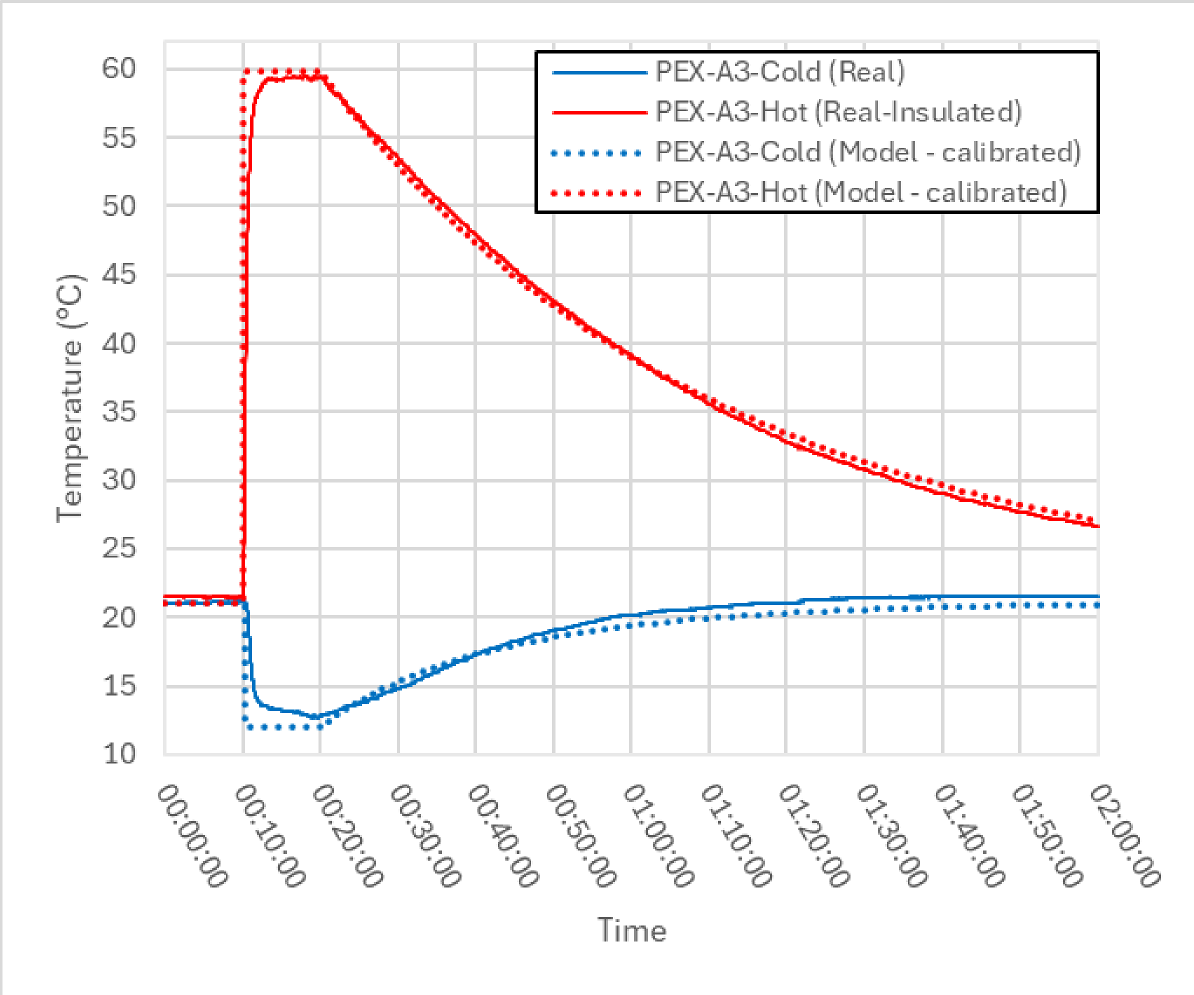


Figure S13. Shower PEX-A3. Temperature vs Time measured, modelled with radial and axial conduction and convection (calibrated for pipe PEX-A1-Cold). Hot shower pipe is insulated.

PEX-B3

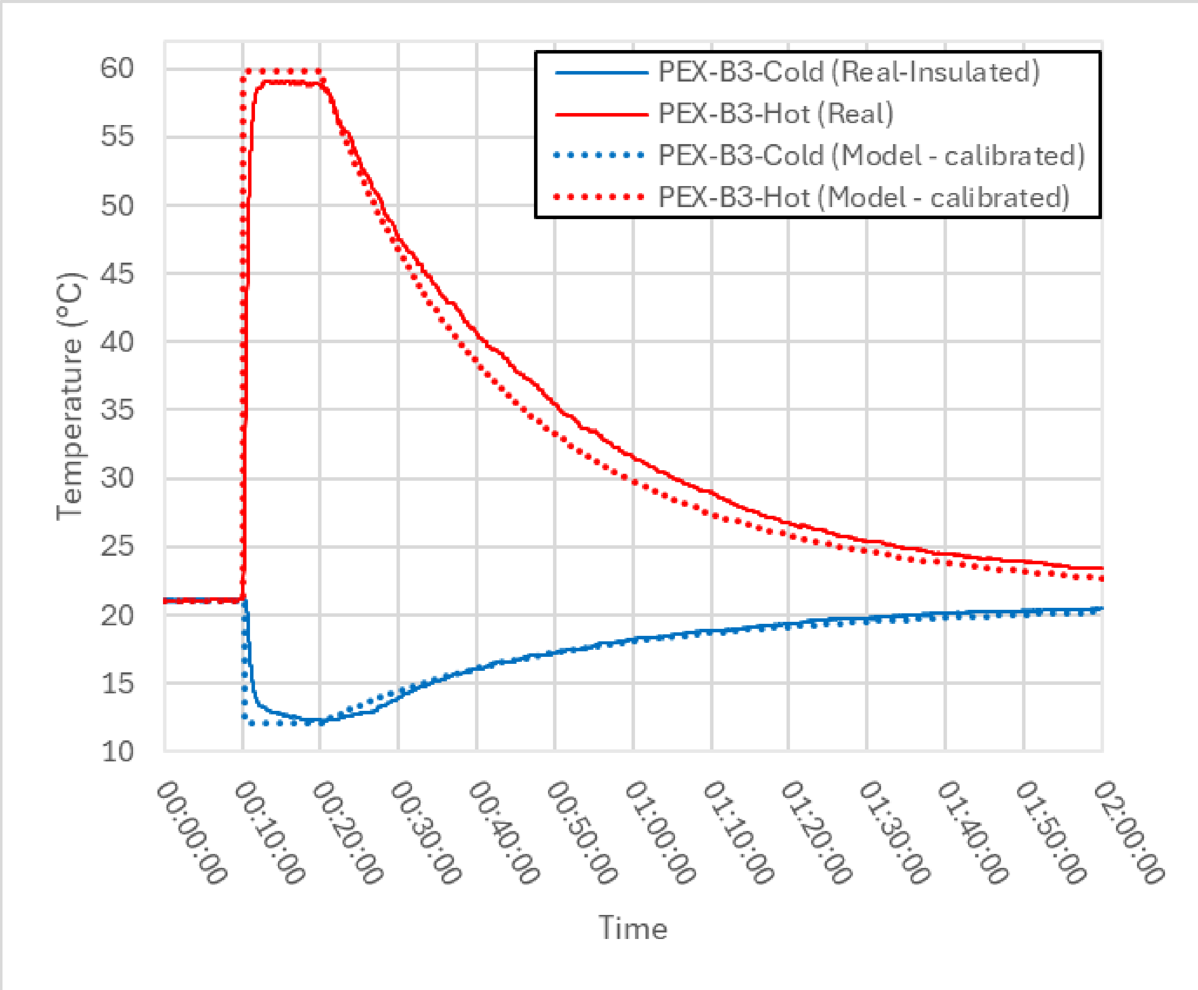


Figure S14. Shower PEX-B3. Temperature vs Time measured, modelled with radial and axial conduction and convection (calibrated for pipe PEX-A1-Cold). Cold shower pipe is insulated.

PEX-C3

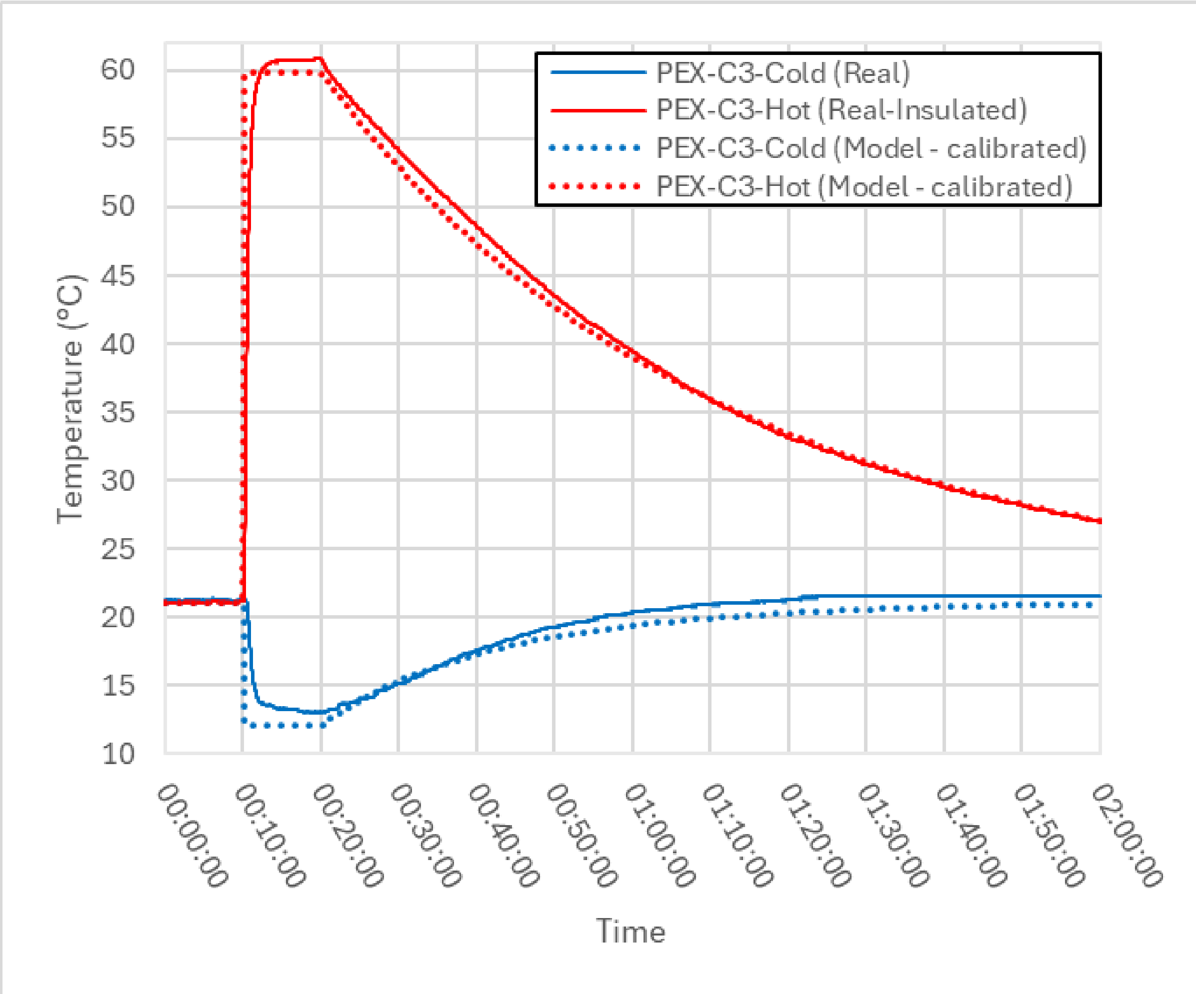


Figure S15. Shower PEX-C3. Temperature vs Time measured, modelled with radial and axial conduction and convection (calibrated for pipe PEX-A1-Cold). Hot shower pipe is insulated.

Cu-A3

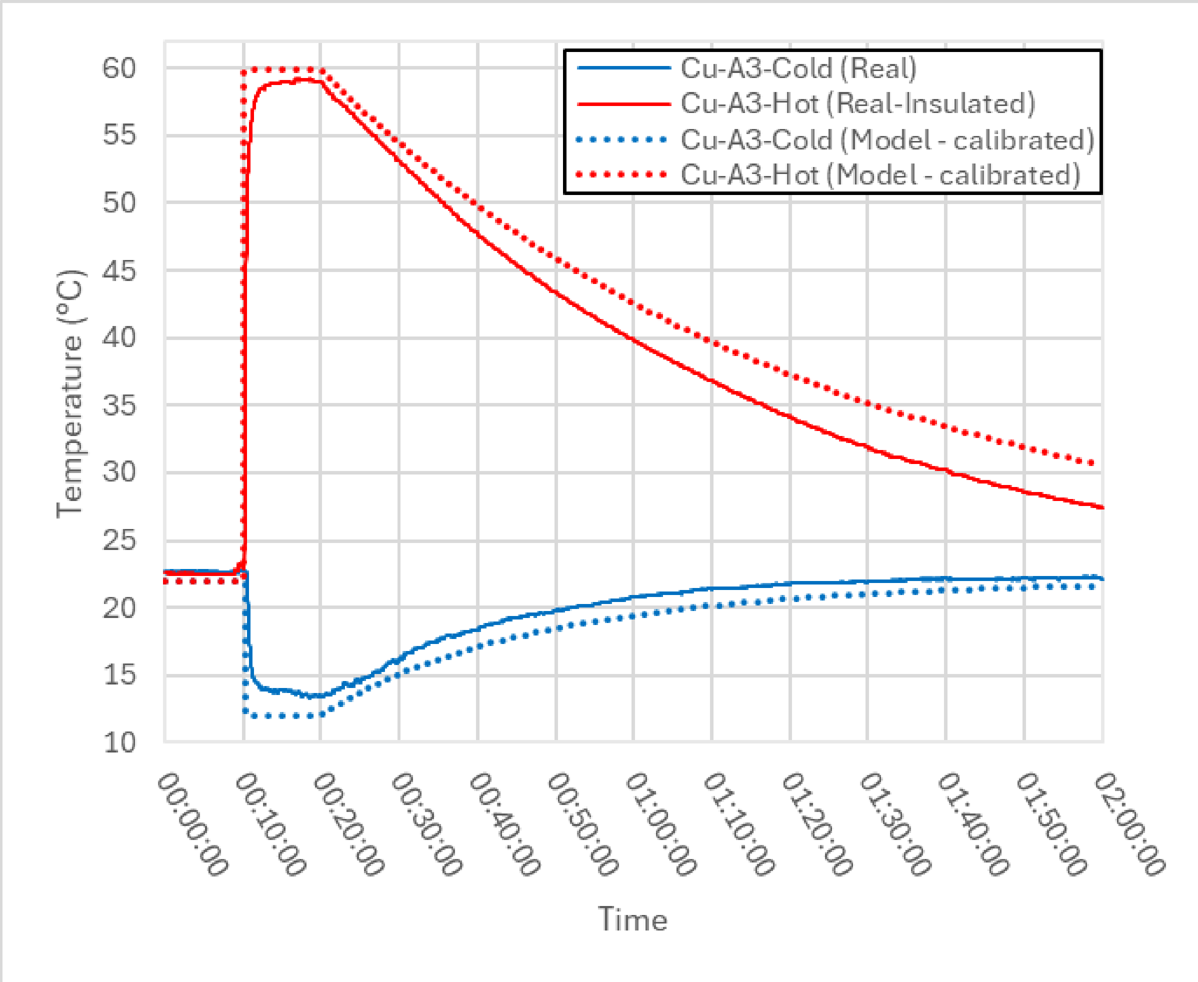


Figure S16. Shower Cu-A3. Temperature vs Time measured, modelled with radial and axial conduction and convection (calibrated for pipe PEX-A1-Cold). Hot shower pipe is insulated.

Cu-B3

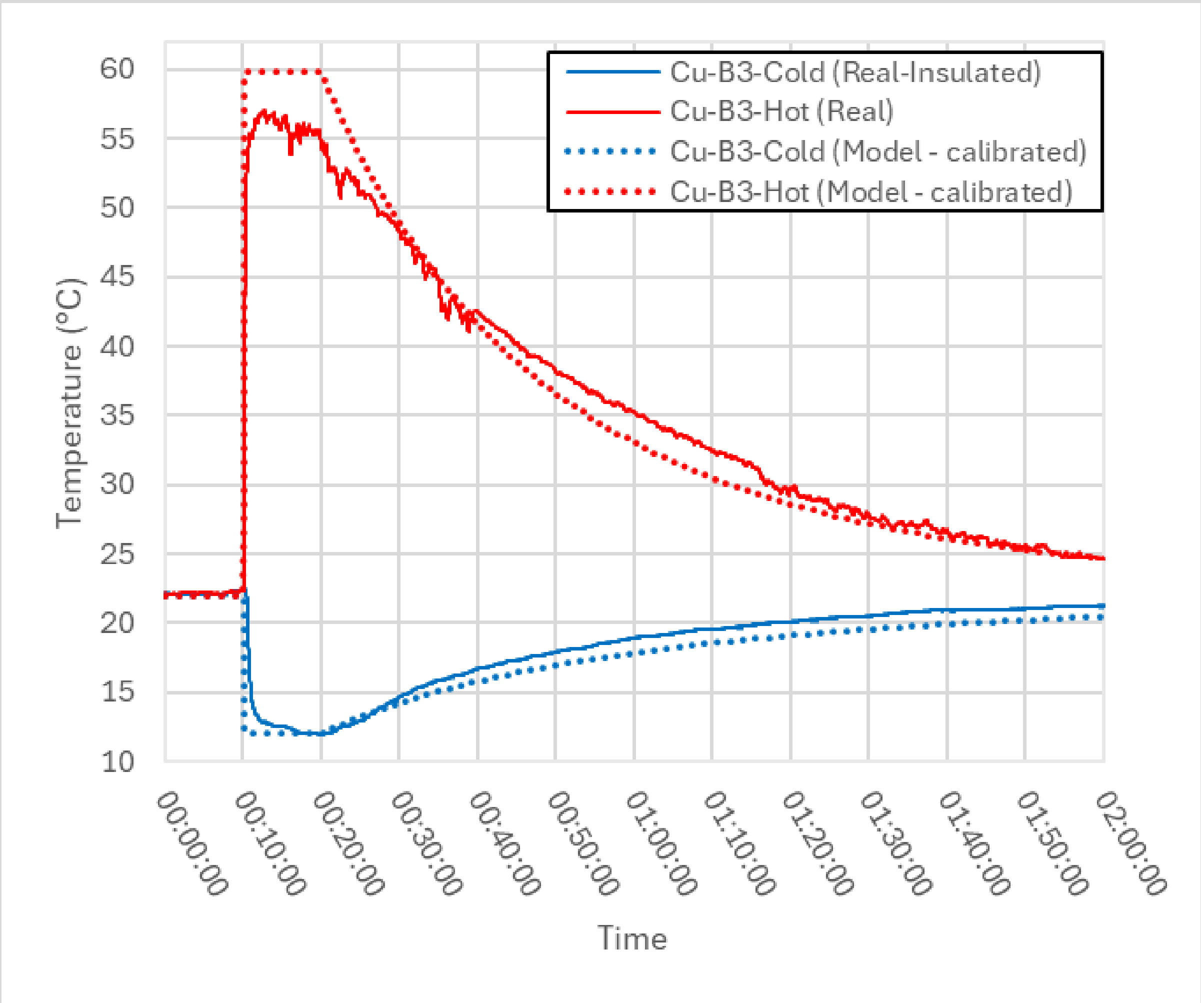


Figure S17. Shower Cu-B3. Temperature vs Time measured, modelled with radial and axial conduction and convection (calibrated for pipe PEX-A1-Cold). Cold shower pipe is insulated.

Cu-C3

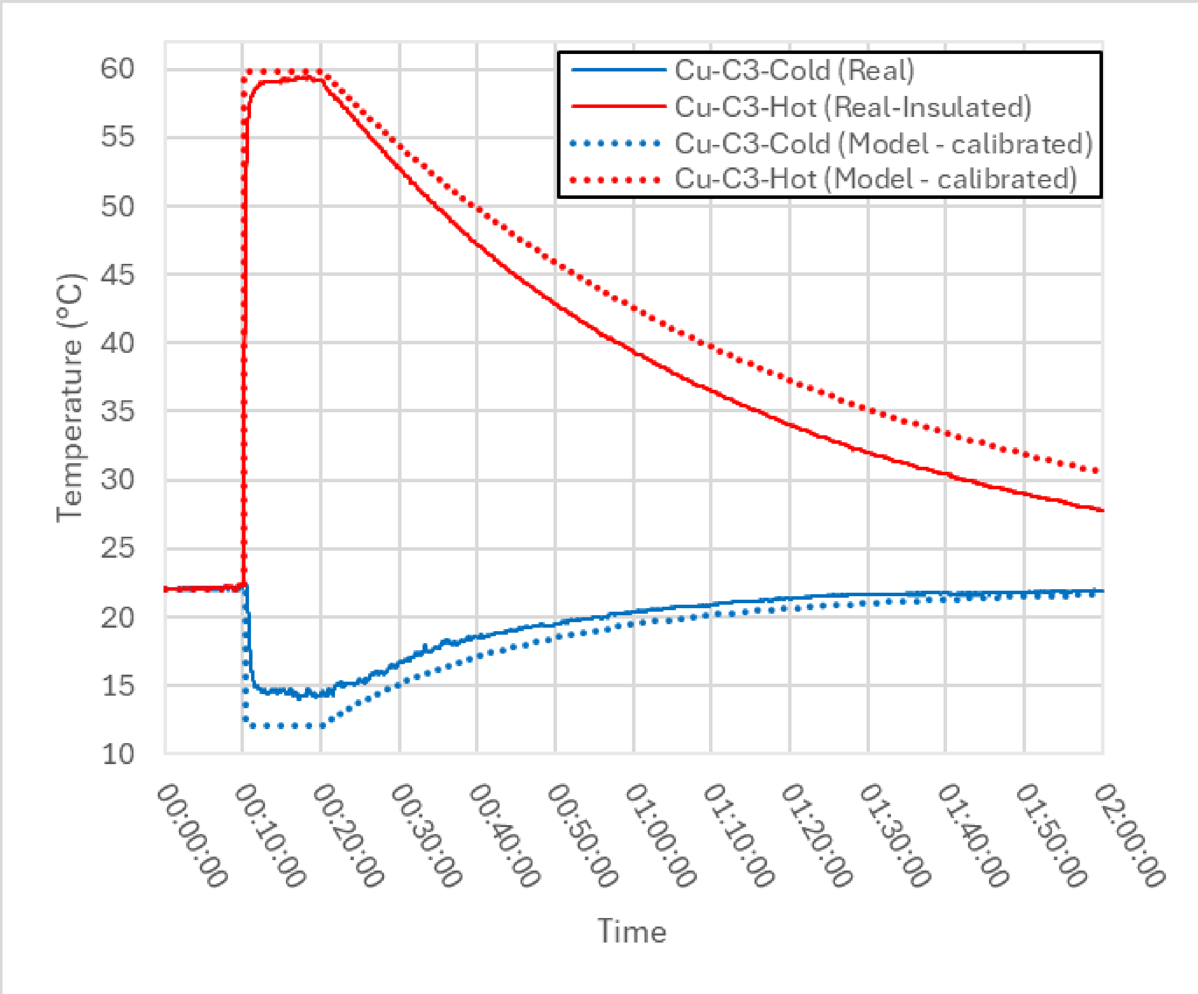


Figure S18. Shower Cu-C3. Temperature vs Time measured, modelled with radial and axial conduction and convection (calibrated for pipe PEX-A1-Cold). Hot shower pipe is insulated.

COMPARISON

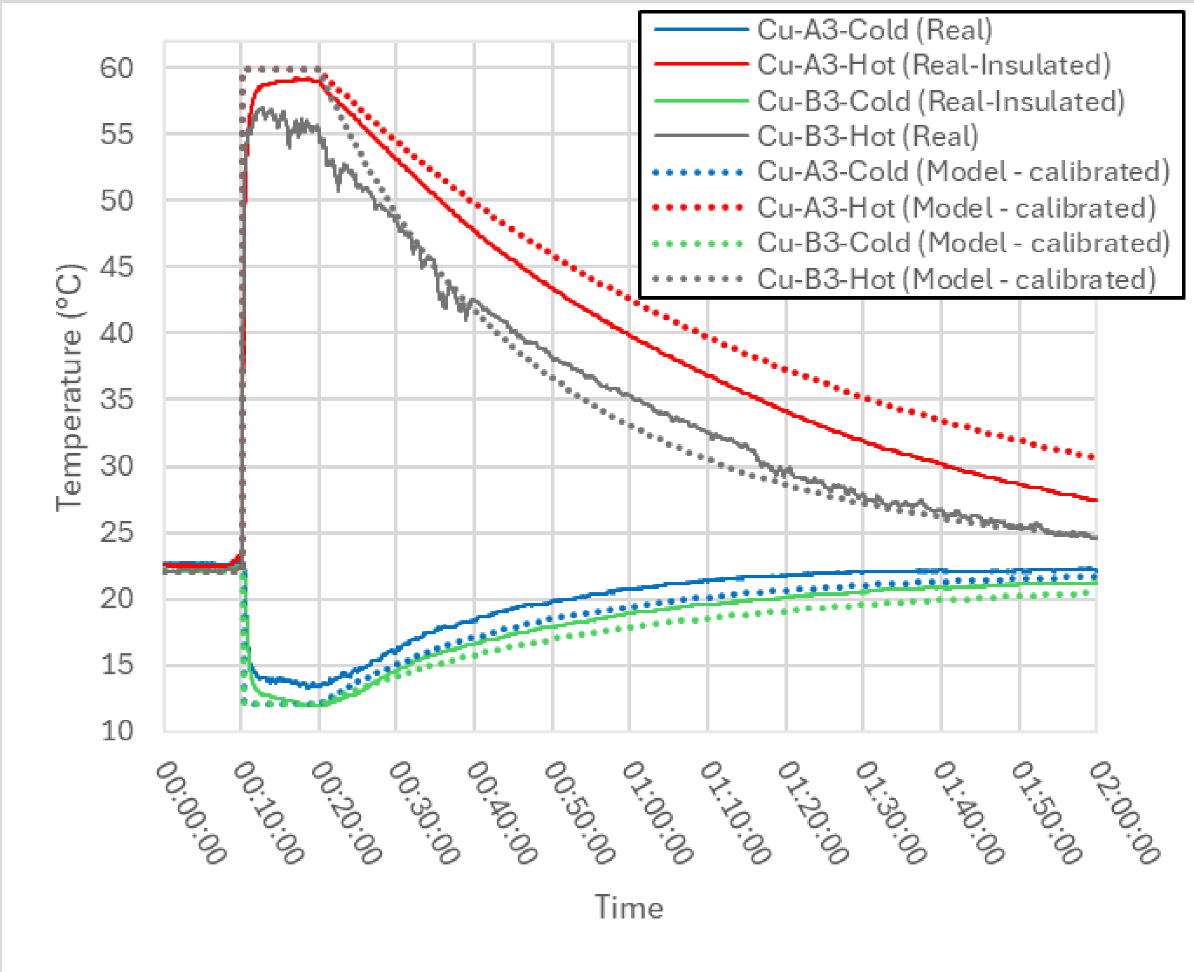


Figure S19. Shower Cu-A3 versus shower Cu-B3. The hot shower pipe is insulated for Cu-A3, while the cold shower pipe is insulated for Cu-B3.

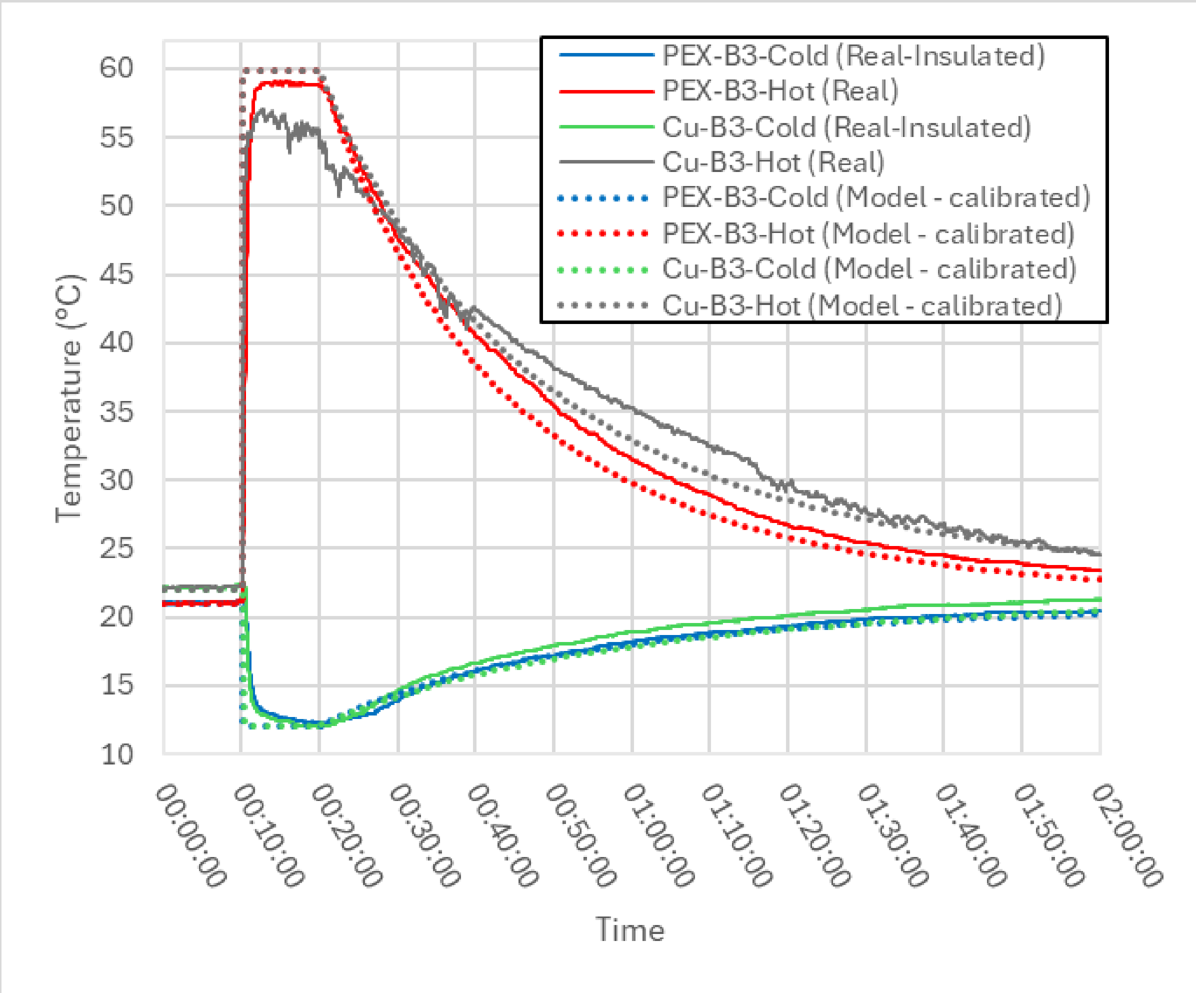


Figure S20. Shower PEX-B3 versus shower Cu-B3. The cold shower pipe is insulated for both showers.

LOCAL SENSITIVITY ANALYSIS

The cooling and heating curves observed on both PEX and copper pipes seemed to behave in a very similar way. In fact, both the model and the measurements showed that the PEX pipes heated and cooled at a slightly faster rate, which was the opposite of what was expected initially by simply comparing their thermal conductivities. *Figure S21* shows a breakdown of the thermal resistance (R_{total}) into its components for pipe PEX-A1-Hot and pipe Cu-A1-Hot and the resulting heat flowrate ($\dot{Q}$) from minute 20 onwards (where the water flow stops).

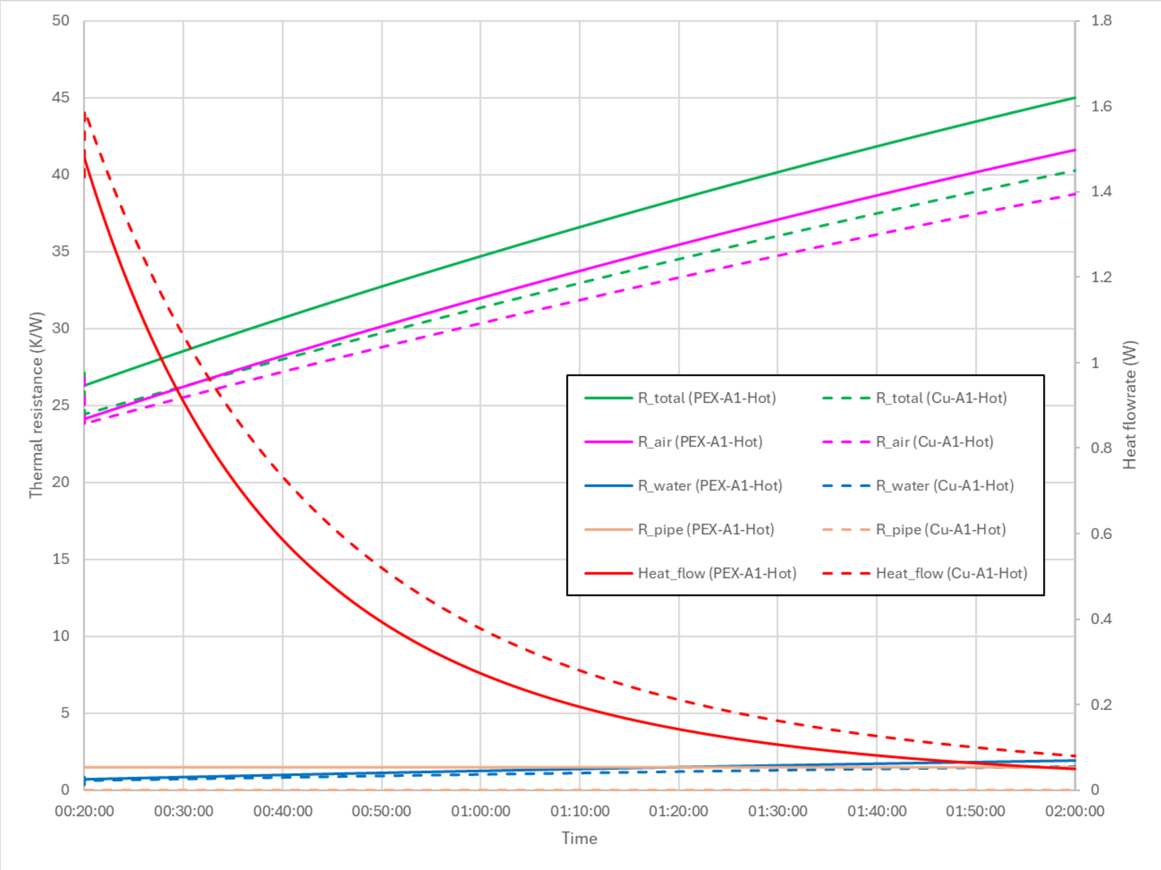


Figure S21. Comparison of thermal resistance (left axis) vs time and heat flowrate vs time (right axis) between pipe PEX-A1-Hot and pipe Cu-A1-Hot

The results for R_{pipe} agree with the initial expectation, being many times larger for PEX than copper, not only because of its lower thermal conductivity but also because its wall thickness was 2.5 mm, compared to 1.5 mm of the copper pipes. R_{total} also seems to agree with the initial expectation that the PEX pipes would have more thermal resistance and, therefore, less overall heat flowrate in the radial direction for similar temperature differences than the copper pipes. However, the largest contributor in both cases is R_{air}, which depends largely on the external diameter, that happens to be the same for both PEX and copper pipes tested ($18\,mm$). The latter explains why the curves are similar, since R_{air} dominates for both rigs overshadowing the large difference between R_{pipe}, which depends on wall thickness and thermal conductivity. Radial heat flowrate also agrees with the expectation, always being lower for PEX with similar temperature gradients in the radial direction.

A hypothetical vertical pipe ($\theta = 90°$) with $L = 0.1m$, constant external diameter of $18\,mm$ (like the PEX and copper pipes tested in the rigs), no net water flow, an initial temperature of 60°C, and a room temperature of 20°C ($\Delta T = 40°C$) was modelled to understand how sensitive are the thermal resistance, heat flowrate, and cooling time, to changes in pipe material (thermal conductivity) and pipe wall thickness. The results of thermal resistance show that, for a constant external diameter of $18\,mm$ and other fixed conditions mentioned above, the resistance from air (R_{air}) is always dominant and turns almost constant for any wall thickness (since $d_{external}$ is kept constant), and any $k_{pipe} \geq 0.3\,W/(m \cdot K)$ approximately, as seen in *Figure S22*.

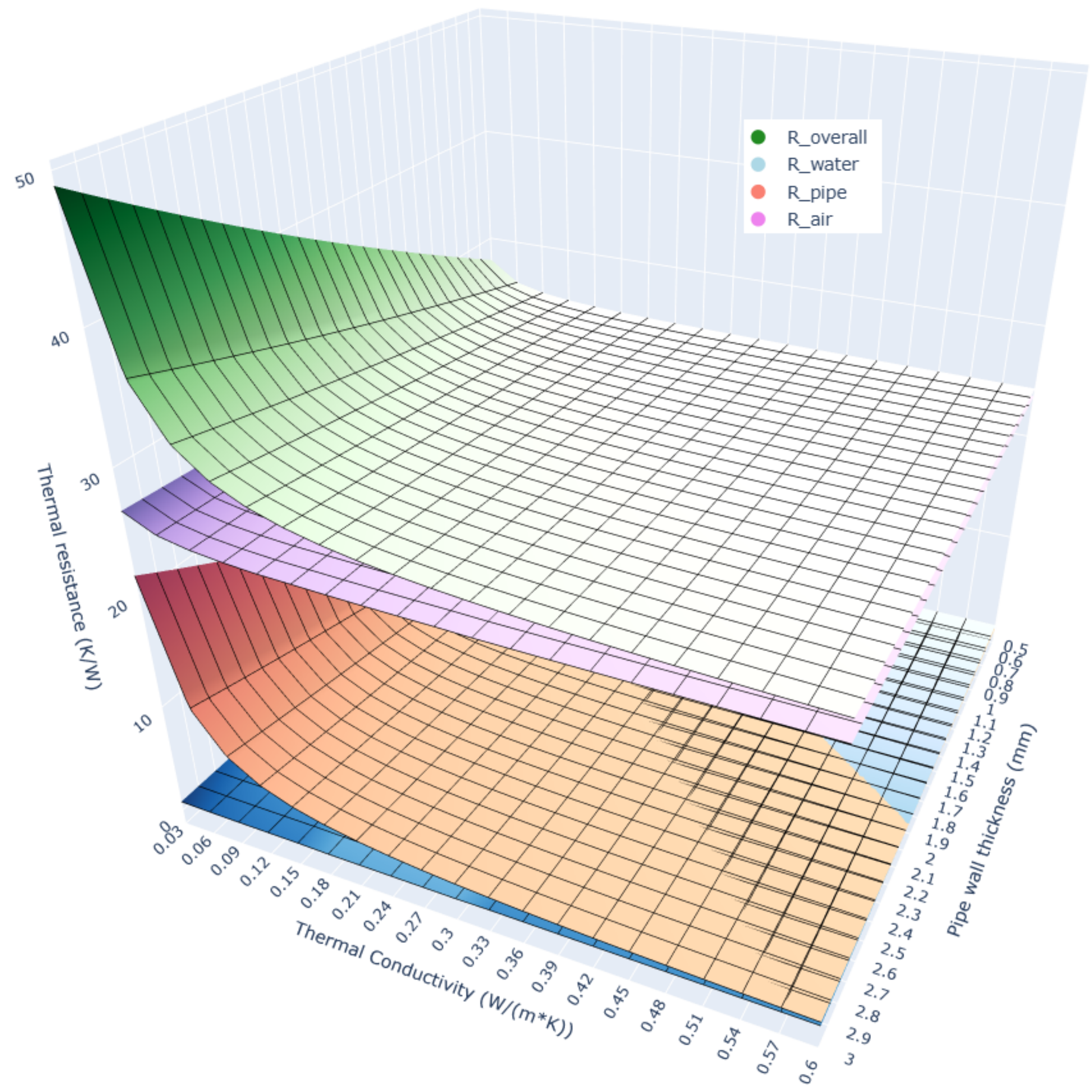


Figure S22. Thermal resistance for different values of thermal conductivity and pipe wall thickness, keeping a constant external diameter of $18mm$, $L = 0.1m$, $\theta = 90°$, $\Delta T = 40°C$ (cooling) and no water flow.

This explains why for similar temperature gradients during the tests, the thermal resistance is also very similar and not very sensitive to the change in thermal conductivities (both PEX and copper are above $0.3\,W/(m * K)$) or pipe wall thickness (2.5mm for PEX and 1.5mm for copper). In consequence, for the same fixed temperature gradient, the heat flowrate also shows to be the same for the wall thickness and thermal conductivity ranges selected, as seen in *Figure S23*. No greater values of thermal conductivity were plotted because the behaviour didn't change. This is because increasing thermal conductivity further only decreases the already negligible thermal resistance from the pipe wall (R_{pipe}) at this scale.

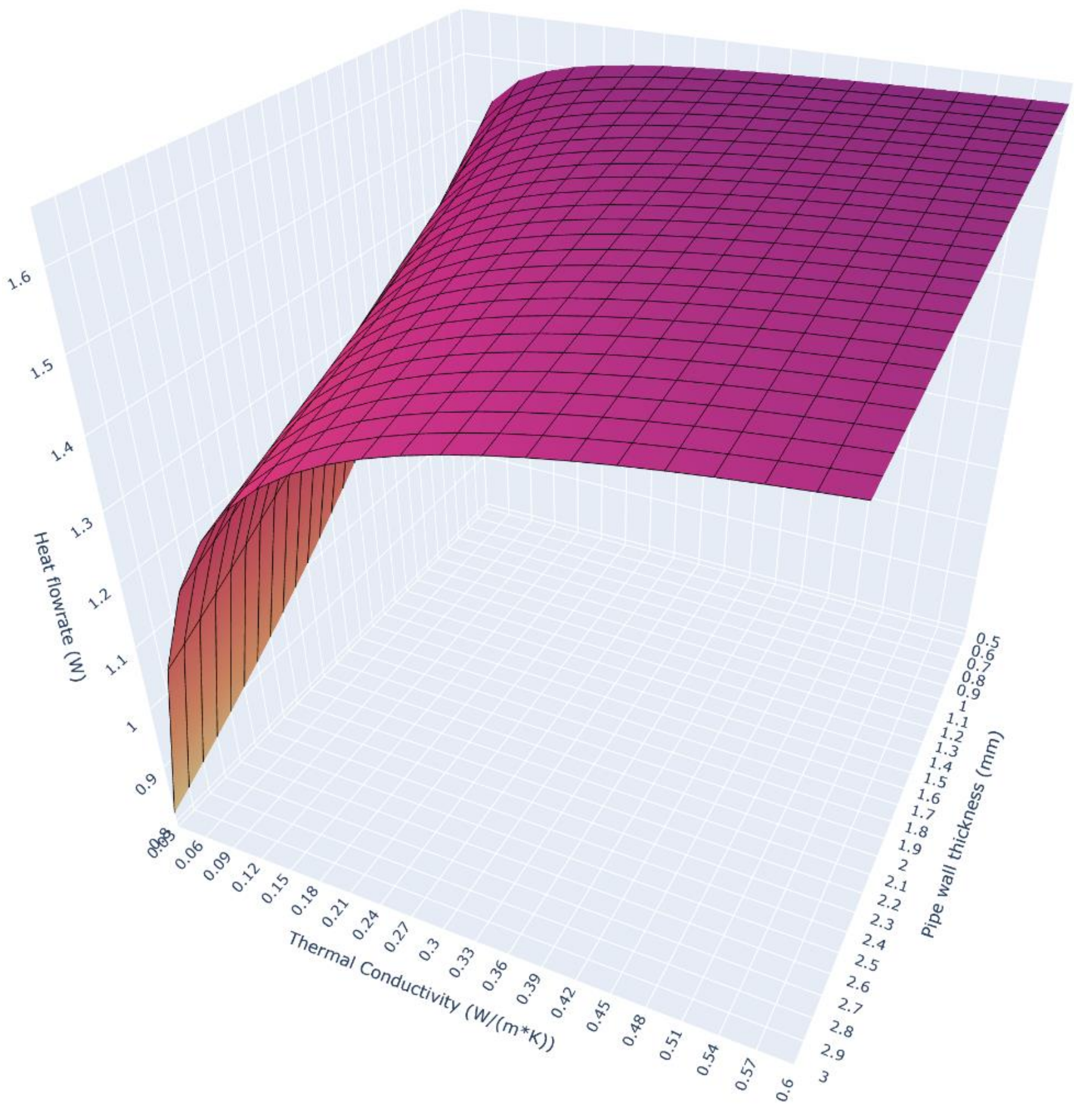


Figure S23. Heat flowrate for different values of thermal conductivity and pipe wall thickness, keeping a constant external diameter of $18mm, L = 0.1m, \theta = 90°, \Delta T = 40°C$ (cooling) and no water flow.

Still, even if the temperature gradients were kept the same during the tests, the heat flowrate would also be almost the same, but always slightly lower for PEX, as expected initially. However, the temperature results show consistently the opposite of what was expected since copper pipes cooled and heated slightly slower than the PEX pipes. To understand this, it is important to recall Equation (6) and Equation (7) where $\tau = C_{p_{water}} \cdot R_{total}$ and the water's heat capacitance ($C_{p_{water}} = \rho_{water} \cdot V_{package} \cdot c_{p_{water}}$) is constant during a certain timestep within a certain water package, but it is a function of the water volume. The PEX and copper pipes used in the rigs have the same external diameter, but different wall thickness, meaning that the copper pipes have a slightly larger inner diameter, changing the volume, heat capacitance, and therefore the value of τ. To illustrate the effect of inner pipe diameter on cooling time (and heating time, by extension), the expected time between temperatures of 25°C and 50°C ($t_{25°C} - t_{50°C}$) was estimated for the same hypothetical pipe and the same thermal conductivity and wall thickness ranges mentioned above. For the set room temperature of 20°C and the initial set hot temperature of 60°C, 50°C corresponds to 75% of the total difference and 25°C corresponds to 12.5%. Therefore, neglecting all axial heat transfer, the time expected to reach 50°C is $t_{50°C} \approx 0.288\tau$ and the time expected to reach 25°C is $t_{25°C} \approx 2.079\tau$ (because $e^{-0.288} \approx 0.75$ and $e^{-2.079} \approx 0.125$). Figure S24 still showed that for $k_{pipe} \geq 0.3\, W/(m \cdot K)$ approximately, there is practically no difference, but the pipe wall thickness did show a significant difference.

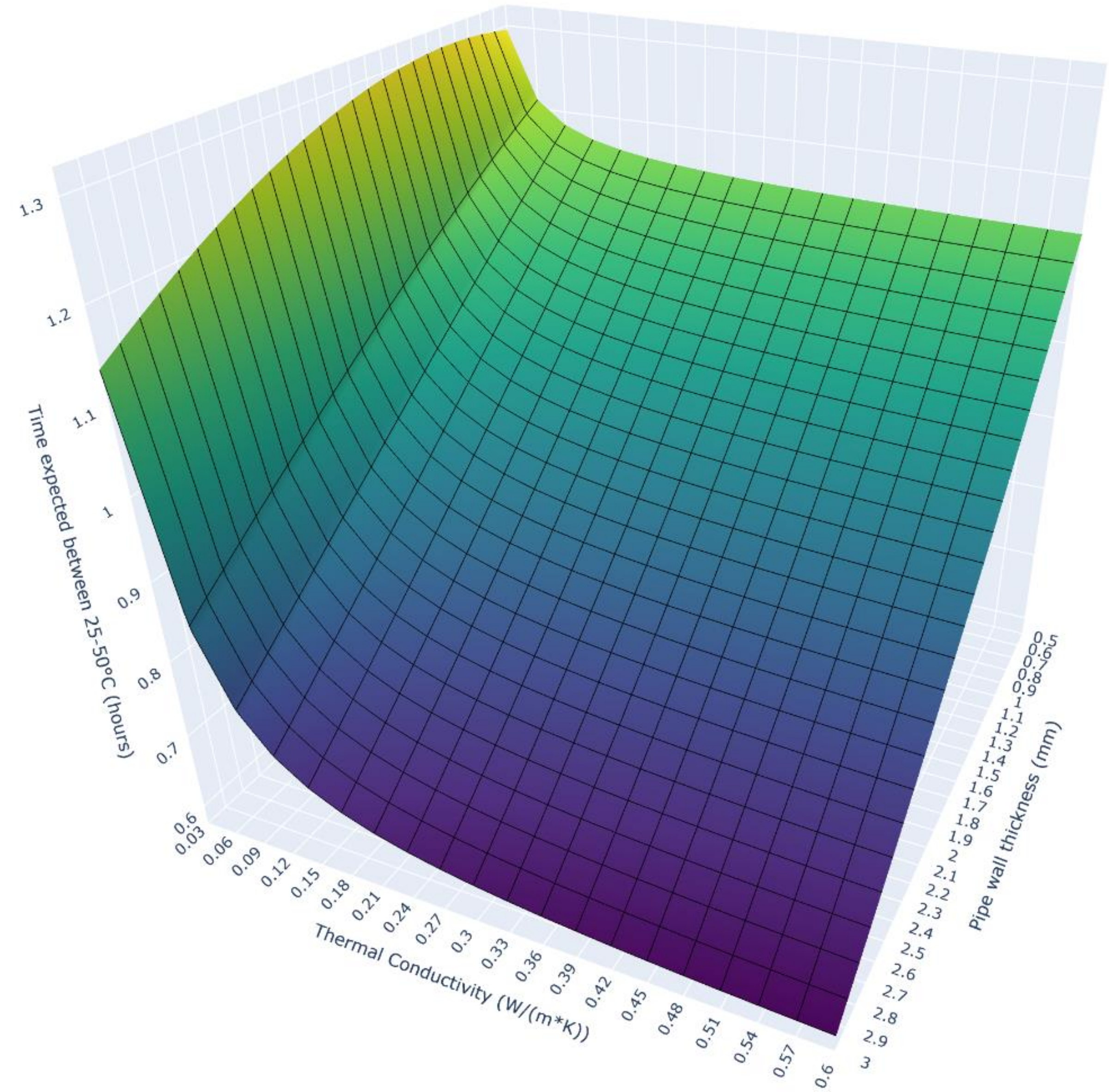


Figure S24. Time expected between 25°C and 50°C for different values of thermal conductivity and pipe wall thickness, keeping a constant external diameter of $18mm, L = 0.1m, \theta = 90°$, cooling from $60°C$ to $20°C$, and no water flow.

This happens because the external diameter is being kept constant (like in the test rigs), but the inner diameter changes, changing the heat capacitance of the water being cooled (or heated). Thus, even if the radial heat flowrate is nearly the same for the same temperature gradients, the heat capacitance or total heat contained by the water within the copper pipes is larger than in the PEX pipes. Therefore, a larger time to cooldown is estimated by the model, contrary to what was initially expected. Also, the pipe material (thermal conductivity) seems to have negligible effect at the scale of these experiments.

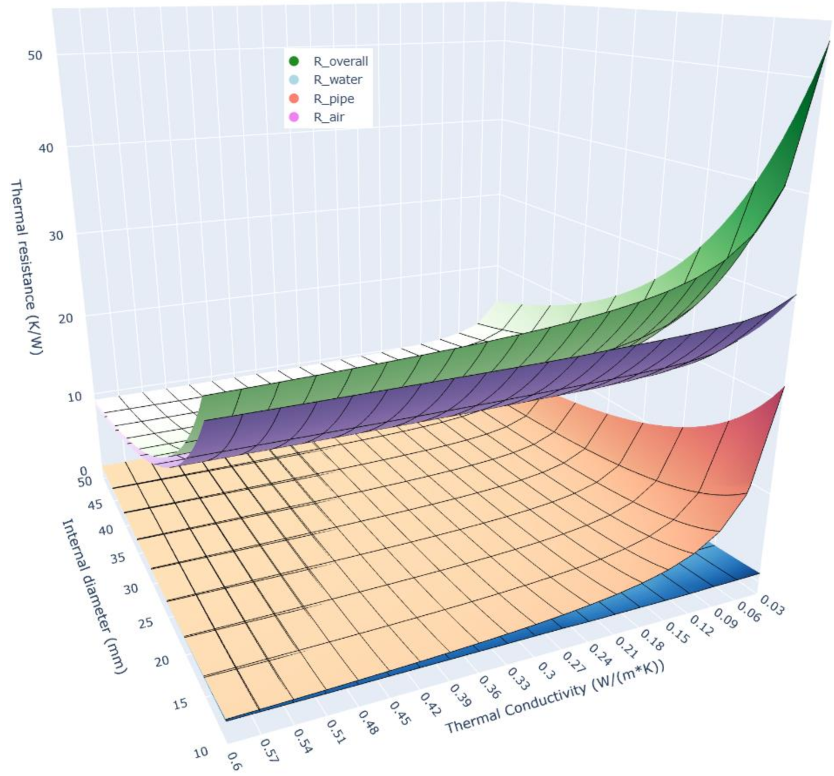
To check for the effect of changing the diameter and the use of insulation, the same pipe from before was modelled, but with the following changes:

a) Constant wall thickness of $2.5\ mm$, varying $d_{internal}$ and k_{pipe}

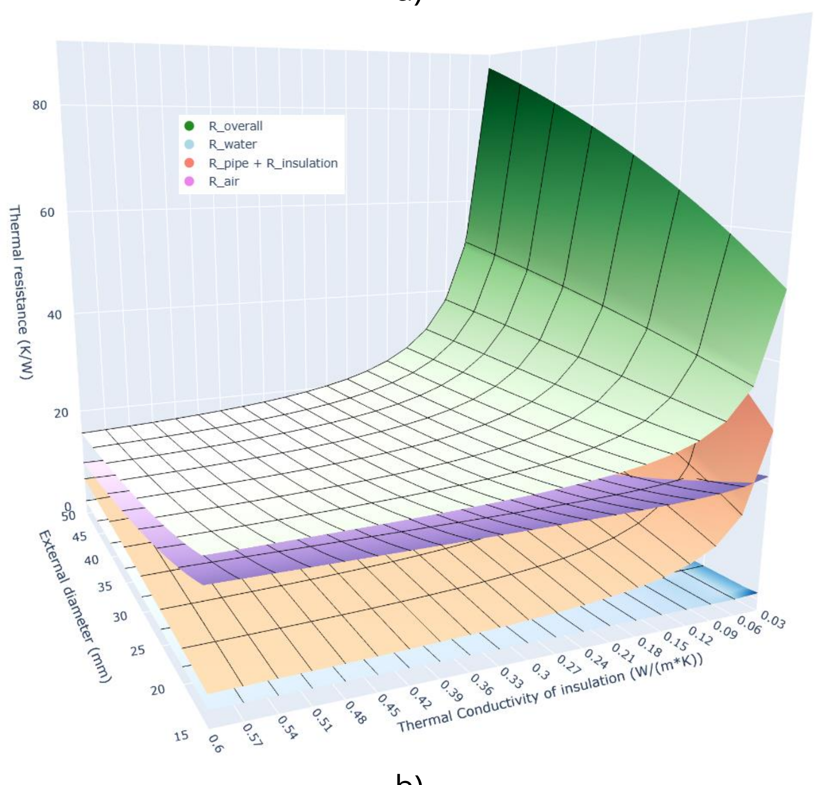
b) Constant wall thickness of $2.5\ mm$, $k_{pipe} = k_{PEX} = 0.35W/(m \cdot K)$, and $d_{internal} = 10mm$, varying insulation thickness (external diameter) and $k_{insulator}$.

Figure S25*a shows that, even for pipe diameters as high as* $50\ mm$ *(~2"),* R_{air} *gets lower because of the larger external pipe area, but still dominates* R_{total} *for* $k_{pipe} \geq 0.3\ W/(m \cdot K)$*. Consequently, the heat flowrate shows an almost linear increase with the inner diameter, but is approximately constant for* $k_{pipe} \geq 0.3\ W/(m \cdot K)$*, as seen in* Figure S26Figure S26. Heat flowrate for different values of: a) pipe thermal conductivity and inner diameter, keeping a constant wall thickness of $2.5mm, L = 0.1m, \theta = 90°, \Delta T = 40°C$ (cooling) and no water flow, and b) thermal conductivity for the insulation and external diameter, keeping a constant pipe wall thickness of $2.5mm$ with $k = k_{PEX}, L = 0.1m, \theta = 90°, \Delta T = 40°C$ (cooling) and no water flow.

a. Nonetheless, just like in the test results, the cooling curve is expected to be slower for bigger inner diameters (larger time in the temperature range), as seen in Figure S27a. This can be explained by the fact that, although the external area increases with $d_{internal}$, the volume of water increases with $d_{internal}^2$. Also, almost no difference can be seen for $k_{pipe} \geq 0.3\ W/(m \cdot K)$, further emphasising that the pipe material may not be very relevant in radial thermal heat transfer for small pipe diameters ($\leq 50mm \sim 2"$) typically used in premise plumbing systems.
Regarding insulation, Figure S25b shows that for very low thermal conductivities, thicker insulation will result in a much higher thermal resistance, as expected, as well as a much lower heat flowrate and slower cooling (and heating) curves, as seen in Figure S26b and Figure S27b, respectively. Nonetheless, as one might expect, for higher thermal conductivities (e.g. for non-insulating materials like PEX or copper), the increase in cross-section thickness, or external diameter, shows the same effect as with increasing the internal diameter, reducing thermal resistance due to increasing the external area perpendicular to the heat flow while not adding much thermal resistance from the cross-section itself ($R_{pipe} + R_{insulation}$). The difference here is that the water volume is not increasing since the inner diameter is set constant at $10mm$, so the cooling time is predicted to be slightly lower even though the cross-section is overall larger, as seen in Figure S27b for $k_{insulator} \geq 0.3\ W/(m * K)$, approximately.

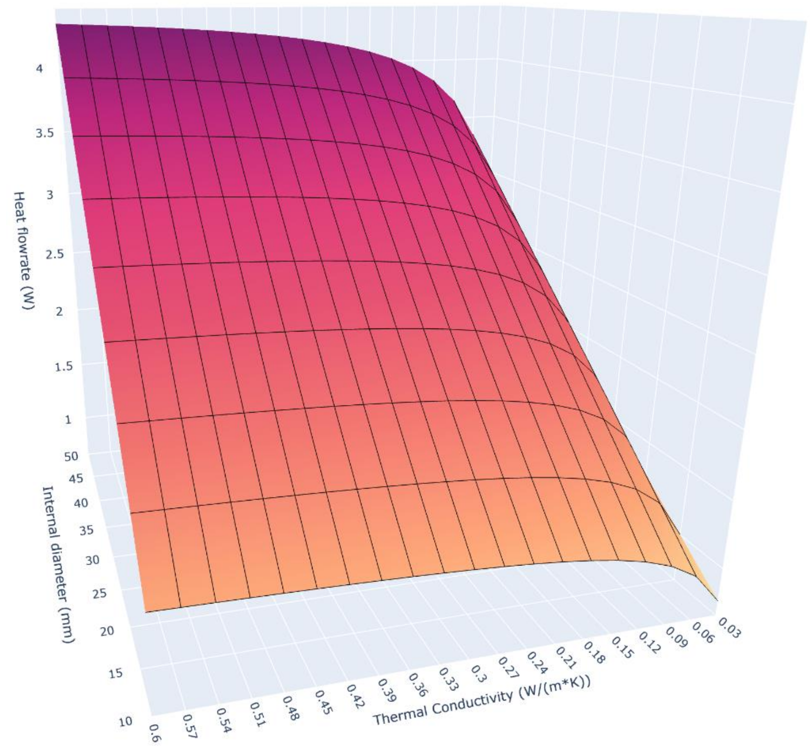


a)

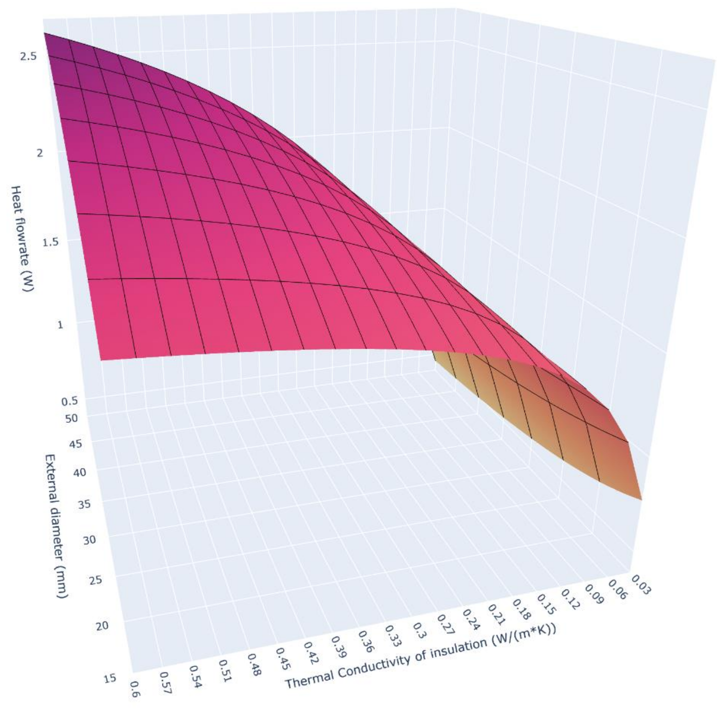


b)

Figure S25. Thermal resistance for different values of: a) pipe thermal conductivity and inner diameter, keeping a constant wall thickness of $2.5mm, L = 0.1m, \theta = 90°, \Delta T = 40°C$ (cooling) and no water flow, and b) thermal conductivity for the insulation and external diameter, keeping a constant pipe wall thickness of $2.5mm$ with $k = k_{PEX}, L = 0.1m, \theta = 90°, \Delta T = 40°C$ (cooling) and no water flow.

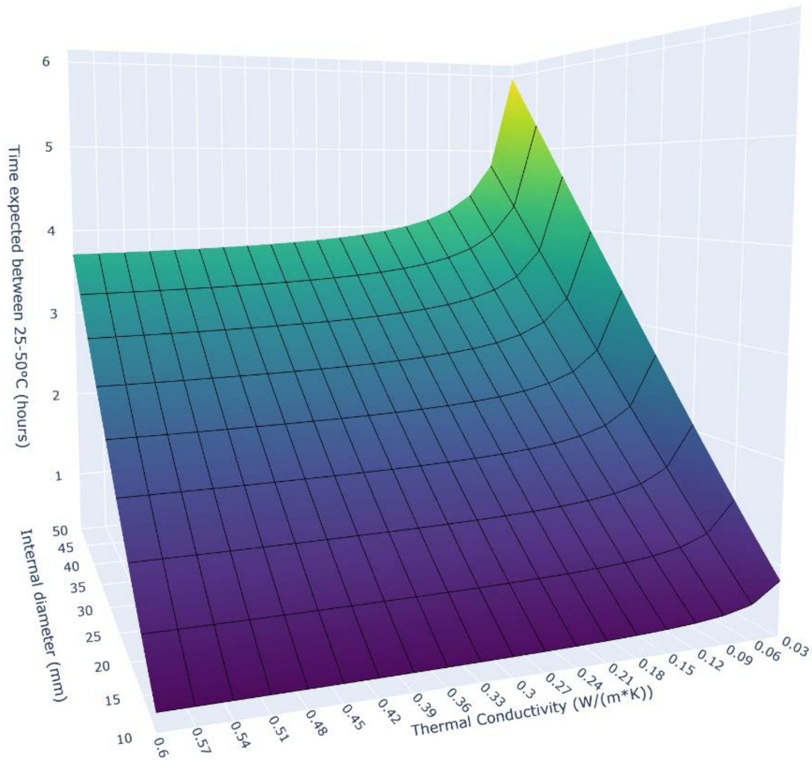


a)

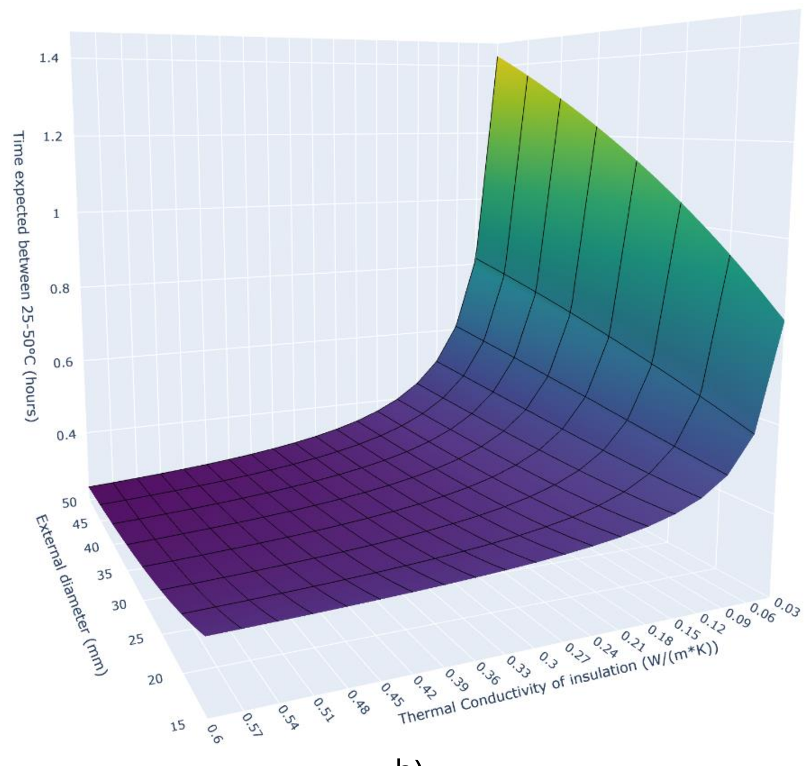


b)

Figure S26. Heat flowrate for different values of: a) pipe thermal conductivity and inner diameter, keeping a constant wall thickness of $2.5mm, L = 0.1m, \theta = 90°, \Delta T = 40°C$ (cooling) and no water flow, and b) thermal conductivity for the insulation and external diameter, keeping a constant pipe wall thickness of $2.5mm$ with $k = k_{PEX}, L = 0.1m, \theta = 90°, \Delta T = 40°C$ (cooling) and no water flow.



a)



b)

Figure S27. Time expected between 25°C and 50°C for different values of: a) pipe thermal conductivity and inner diameter, keeping a constant wall thickness of $2.5mm, L = 0.1m, \theta = 90°$, cooling from 60°C to 20°C, and no water flow, and b) thermal conductivity for the insulation and external diameter, keeping a constant pipe wall thickness of $2.5mm$ with $k = k_{PEX}$, $L = 0.1m, \theta = 90°$, cooling from 60°C to 20°C, and no water flow.