# Development of a Probe for Measuring the Thermal Properties of Building Materials In-situ

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PLEA2006 Conference, Geneva

# Introduction

- ➢ Many building materials have unknown thermal properties:
  - novel (environmentally friendly)
  - dependent on in-situ construction
  - impacted by moisture content
  - composition not known (vernacular)

# General Goal

- Development of a *Thermal Probe* apparatus for in-situ measurements of:
  - thermal conductivity ($\lambda$)
  - thermal diffusivity ($\alpha$)

- Aims and objectives:
  - fast but accurate
  - relatively non-destructive
  - economical
  - transportable

# Aim of this Presentation

- Present Thermal Probe apparatus and measurement process as developed at University of Plymouth
- Show some results of field trials
- Discuss areas for further investigation and research

# Thermal Probe Apparatus

- Carbon Trust funded R&D project
- Building on previous efforts (Goodhew and Griffiths)
- Employing commercial systems from other disciplines (Hukseflux probe)

# Theoretical Background

- Based on theory of a line-source in an infinite, homogenous sample

- Blackwell equation (1950s):

$$\Delta T = \frac{Q'}{4\pi\lambda}\left[\ln\tau + \left(\ln\left(\frac{4\alpha}{r^2}\right) - \gamma + \frac{2\lambda}{rH}\right) + \left(\frac{1}{\tau}\right)\left(\left(\frac{r^2}{2\alpha}\right)\left[1 - {mc_p\alpha}\big/{\pi.r^2L\lambda}\right]\ln\tau + \left(\frac{r^2}{2\alpha}\right)\left[\ln\left(\frac{4\alpha}{r^2}\right) - \gamma + 1 - \frac{\left[\ln\left(\frac{4\alpha}{r^2}\right) - \gamma + \frac{2\lambda}{rH}\right]mc_p\alpha}{\pi.r^2L\lambda}\right]\right)\right]$$

# Measurement Procedure

- Drill hole (not trivial)
- Insert probe (not trivial either)
- Heat-up probe and measure temperature rise in the material
- Data analysis to derive:
  - thermal conductivity (λ)
  - thermal diffusivity  (α)

  using an iterative line fitting process

# Results

Over 600 measurements taken

Over 100 on site in real buildings in

Cornwall, Devon, Scotland, SE England

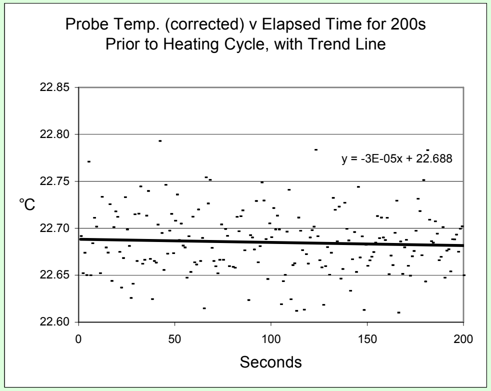
# Results

The University of Plymouth

# Results

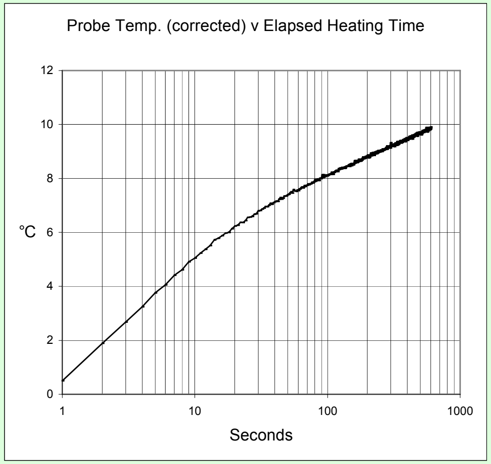
Oak, across the grain

| PT1000 t (°C) | Heater (mV) | PT1000 Res | emf (mV) | TK t (°C) | emf t diff (°C) | PT1000 & emf (°C) | Heat Cycle (s) | CTD | Power (W/m) | ln(t) |
|---|---|---|---|---|---|---|---|---|---|---|
| 22.8322078 | 203.9486 | 1087.904 | -0.00738 | 28.26639 | -0.18274 | 22.64947 | 172 | | | |
| 22.8064935 | 203.9453 | 1087.805 | -0.00551 | 28.26778 | -0.13644 | 22.67005 | 173 | | | |
| 22.8418182 | 203.9495 | 1087.941 | -0.00671 | 28.26791 | -0.16615 | 22.67567 | 174 | | | |
| 22.8366234 | 203.9474 | 1087.921 | -0.00563 | 28.21247 | -0.13941 | 22.69722 | 175 | | | |
| 22.841039 | 203.9418 | 1087.938 | -0.00443 | 28.22427 | -0.10969 | 22.73135 | 176 | | | |
| 22.84 | 203.9432 | 1087.934 | -0.00492 | 28.24669 | -0.12183 | 22.71817 | 177 | | | |
| 22.8506494 | 203.9477 | 1087.975 | -0.00725 | 28.22381 | -0.17952 | 22.67113 | 178 | | | |
| 22.8332468 | 203.944 | 1087.908 | -0.00331 | 28.19429 | -0.08196 | 22.75129 | 179 | | | |
| 22.8384416 | 203.9496 | 1087.928 | -0.00788 | 28.22106 | -0.19512 | 22.64332 | 180 | | | |
| 22.8633766 | 203.9466 | 1088.024 | -0.00324 | 28.11546 | -0.08023 | 22.78315 | 181 | | | |
| 22.8446753 | 203.9462 | 1087.952 | -0.00548 | 28.05525 | -0.13569 | 22.70898 | 182 | | | |
| 22.8348052 | 203.9504 | 1087.914 | -0.006 | 28.22202 | -0.14857 | 22.68624 | 183 | | | |
| 22.8350649 | 203.9406 | 1087.915 | -0.00607 | 28.22409 | -0.1503 | 22.68476 | 184 | | | |
| 22.8257143 | 203.9466 | 1087.879 | -0.00478 | 28.2166 | -0.11836 | 22.70735 | 185 | | | |
| 22.8309091 | 203.9423 | 1087.899 | -0.00552 | 28.20864 | -0.13668 | 22.69423 | 186 | | | |
| 22.8337662 | 203.9451 | 1087.91 | -0.00678 | 28.18253 | -0.16788 | 22.66588 | 187 | | | |
| 22.8223377 | 203.9477 | 1087.866 | -0.00617 | 28.21409 | -0.15278 | 22.66956 | 188 | | | |
| 22.8332468 | 203.9503 | 1087.908 | -0.00533 | 28.21884 | -0.13198 | 22.70127 | 189 | | | |
| 22.8290909 | 203.9429 | 1087.892 | -0.00734 | 28.25343 | -0.18175 | 22.64734 | 190 | | | |
| 22.8293506 | 203.9481 | 1087.893 | -0.00619 | 28.25353 | -0.15327 | 22.67608 | 191 | | | |
| 22.841039 | 203.9446 | 1087.938 | -0.0066 | 28.25706 | -0.16342 | 22.67761 | 192 | | | |
| 22.8280519 | 203.9465 | 1087.888 | -0.00703 | 28.28741 | -0.17407 | 22.65398 | 193 | | | |
| 22.8412987 | 203.9471 | 1087.939 | -0.00618 | 28.24654 | -0.15303 | 22.68827 | 194 | | | |
| 22.8324675 | 203.9485 | 1087.905 | -0.00583 | 28.25111 | -0.14436 | 22.68811 | 195 | | | |
| 22.8361039 | 203.9446 | 1087.919 | -0.00577 | 28.15058 | -0.14287 | 22.69323 | 196 | | | |
| 22.8254545 | 203.9445 | 1087.878 | -0.00608 | 28.25947 | -0.15055 | 22.6749 | 197 | Prior Slope | | |
| 22.8277922 | 203.9435 | 1087.887 | -0.00518 | 28.12353 | -0.12827 | 22.69953 | 198 | -3.5E-05 | | |
| 22.8179221 | 203.9386 | 1087.849 | -0.00468 | 28.26424 | -0.11589 | 22.70204 | 199 | | | |
| 22.8303896 | 203.9408 | 1087.897 | -0.00729 | 28.26719 | -0.18051 | 22.64988 | 200 | | | |
| 22.8233766 | 203.9488 | 1087.87 | -0.00699 | 28.27254 | -0.17308 | 22.65029 | 0 | 0 | | |
| 22.8103896 | 202.3171 | 1087.82 | 0.01527 | 28.79583 | 0.378116 | 23.18851 | 1 | 0.50444 | | 0 |
| 22.8381818 | 202.3158 | 1087.927 | 0.07 | 30.03325 | 1.733298 | 24.57148 | 2 | 1.88745 | | 0.69315 |
| 22.834026 | 202.3189 | 1087.911 | 0.10208 | 30.92115 | 2.527653 | 25.36168 | 3 | 2.67768 | | 1.09861 |
| 22.847013 | 202.327 | 1087.961 | 0.1244 | 31.4575 | 3.080294 | 25.92731 | 4 | 3.24335 | | 1.38629 |
| 22.8322078 | 202.3271 | 1087.904 | 0.146 | 31.96749 | 3.615184 | 26.44739 | 5 | 3.76347 | | 1.60944 |
| 22.827013 | 202.3281 | 1087.884 | 0.15784 | 32.25735 | 3.908379 | 26.73539 | 6 | 4.0515 | | 1.79176 |
| 22.8337662 | 202.3259 | 1087.91 | 0.1722 | 32.54422 | 4.26393 | 27.0977 | 7 | 4.41384 | | 1.94591 |
| 22.8371429 | 202.3217 | 1087.923 | 0.18026 | 32.88322 | 4.463495 | 27.30064 | 8 | 4.61681 | | 2.07944 |
| 22.8381818 | 202.328 | 1087.927 | 0.1921 | 33.0355 | 4.756665 | 27.59485 | 9 | 4.91106 | | 2.19722 |
| 22.8381818 | 202.3246 | 1087.927 | 0.1977 | 33.25393 | 4.895329 | 27.73351 | 10 | 5.04976 | 3.2743 | 2.30259 |
| 22.8514286 | 202.3263 | 1087.978 | 0.20452 | 33.40206 | 5.064142 | 27.91557 | 11 | 5.23185 | 3.27436 | 2.3979 |
| 22.8371429 | 202.324 | 1087.923 | 0.21085 | 33.53848 | 5.220947 | 28.05809 | 12 | 5.37441 | 3.27428 | 2.48491 |
| 22.861039 | 202.3235 | 1088.015 | 0.21527 | 33.69024 | 5.330278 | 28.19132 | 13 | 5.50767 | 3.27427 | 2.56495 |
| 22.8467532 | 202.3257 | 1087.96 | 0.2247 | 33.84619 | 5.563844 | 28.4106 | 14 | 5.72698 | 3.27434 | 2.63906 |
| 22.8415584 | 202.3264 | 1087.94 | 0.2273 | 33.93253 | 5.62825 | 28.46981 | 15 | 5.78623 | 3.27436 | 2.70805 |
| 22.838961 | 202.3288 | 1087.93 | 0.23106 | 33.97813 | 5.721366 | 28.56033 | 16 | 5.87678 | 3.27444 | 2.77259 |
| 22.8244156 | 202.3261 | 1087.874 | 0.23569 | 34.14908 | 5.836087 | 28.6605 | 17 | 5.97699 | 3.27435 | 2.83321 |
| 22.8303896 | 202.3349 | 1087.897 | 0.23639 | 34.16597 | 5.853389 | 28.68378 | 18 | 6.0003 | 3.27464 | 2.89037 |
| 22.8355844 | 202.3283 | 1087.917 | 0.24167 | 34.35994 | 5.984102 | 28.81969 | 19 | 6.13624 | 3.27442 | 2.94444 |
| 22.8353247 | 202.3273 | 1087.916 | 0.24564 | 34.39051 | 6.082407 | 28.91773 | 20 | 6.23432 | 3.27439 | 2.99573 |
| 22.8350649 | 202.3217 | 1087.915 | 0.24698 | 34.49971 | 6.115588 | 28.95065 | 21 | 6.26728 | 3.27421 | 3.04452 |
| 22.8415584 | 202.327 | 1087.94 | 0.25102 | 34.54708 | 6.215588 | 29.05715 | 22 | 6.37381 | 3.27438 | 3.09104 |
| 22.8407792 | 202.3285 | 1087.937 | 0.25072 | 34.59803 | 6.208164 | 29.04894 | 23 | 6.36564 | 3.27443 | 3.13549 |
| 22.8316883 | 202.3292 | 1087.902 | 0.25391 | 34.68688 | 6.287204 | 29.11889 | 24 | 6.43562 | 3.27445 | 3.17805 |
| 22.8483117 | 202.3238 | 1087.966 | 0.25815 | 34.73071 | 6.392098 | 29.24041 | 25 | 6.55717 | 3.27428 | 3.21888 |
| 22.8493506 | 202.3322 | 1087.97 | 0.25845 | 34.76003 | 6.39952 | 29.24887 | 26 | 6.56567 | 3.27455 | 3.2581 |




| t before heat | | Power/m | |
|---|---|---|---|
| 50s mean | 22.6841 | 200s mea | 3.27444 |
| 50s SD: | 0.02929 | 200s SD: | 0.0001 |

12:17:00



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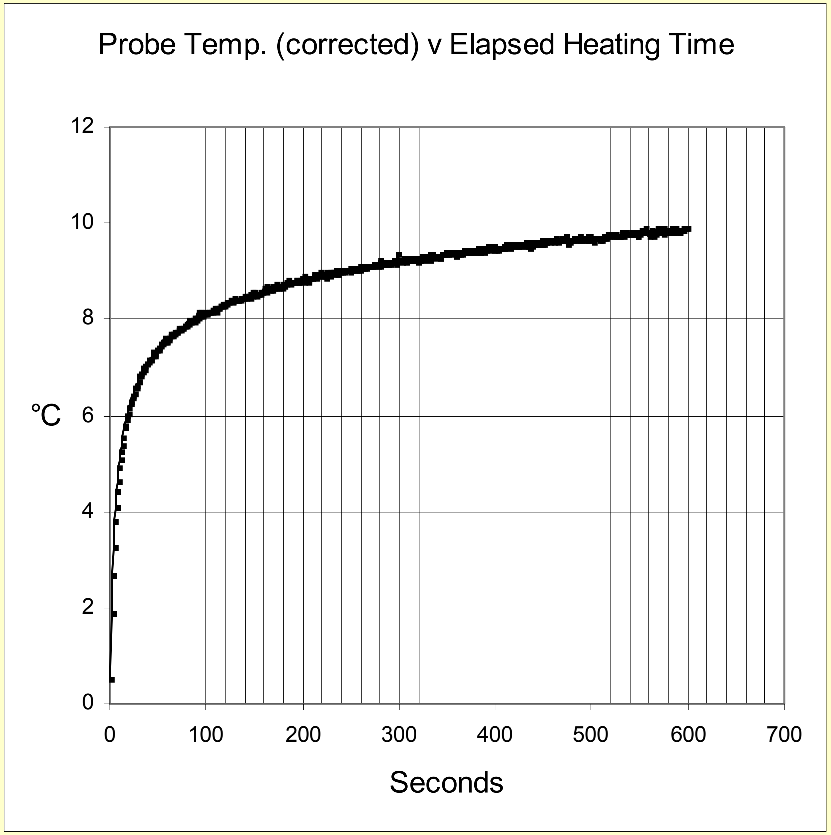
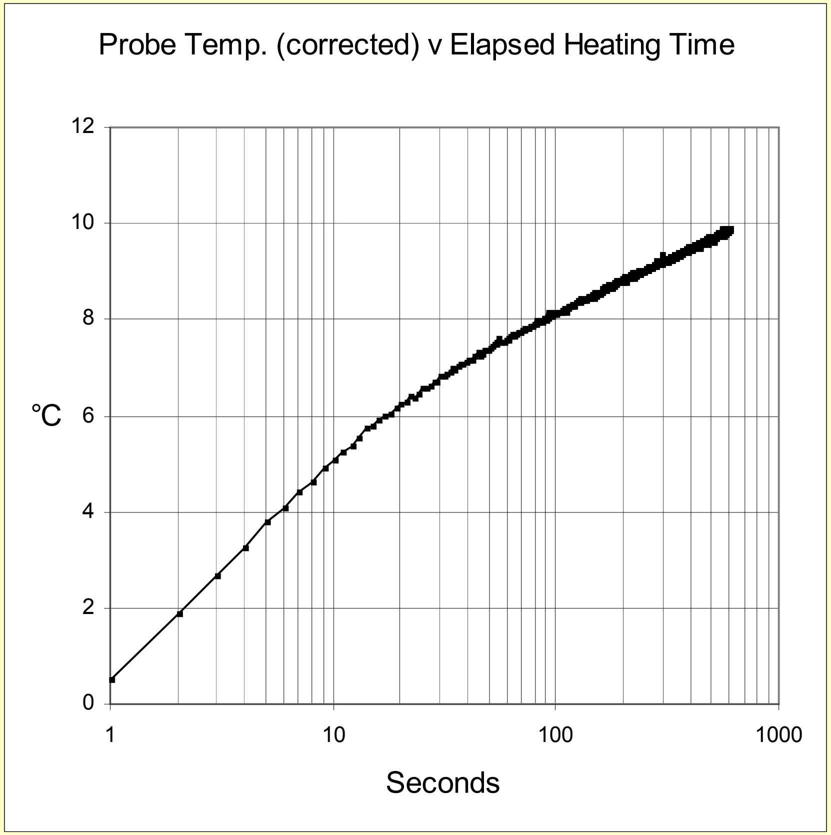
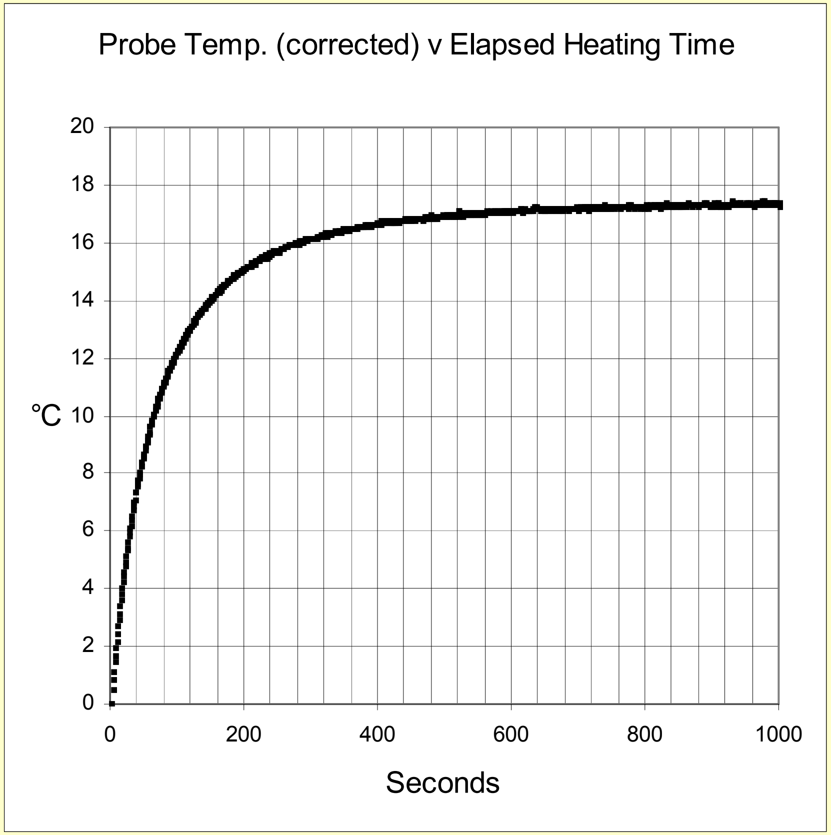
# Results

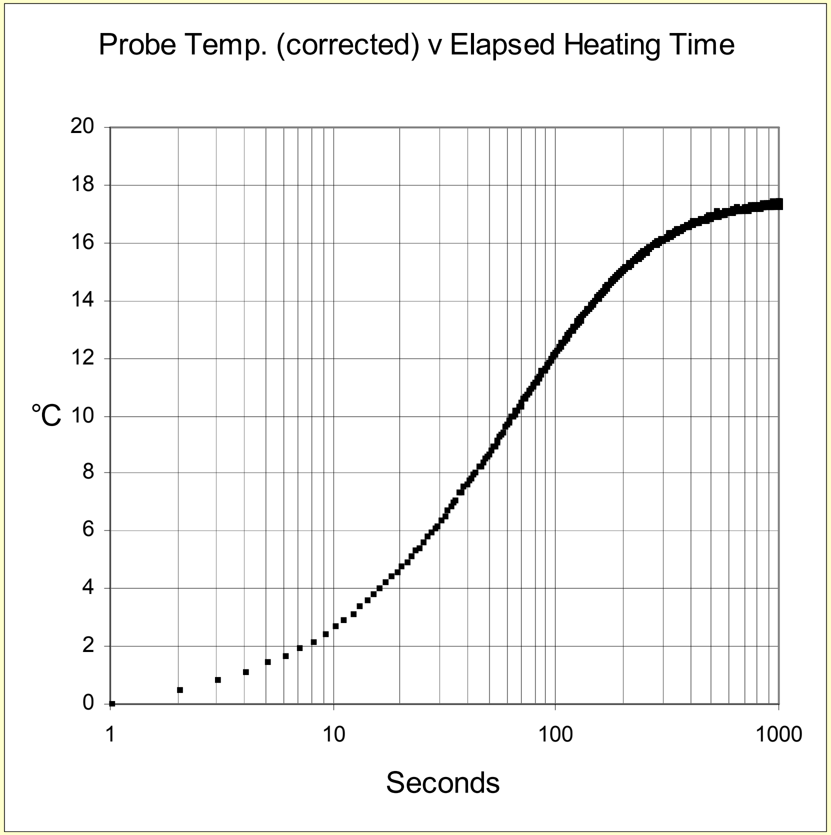



Oak, across the grain

# Results




Phenolic foam

# Results

Solver 4.3 from RG Griffiths (14/04/2001), adapted 25/04/2006

Date 31/08/2006

**AFTER SOLVER**

| | | | |
|---|---|---|---|
| Probe | TP08 Hux | | |
| Probe power | 0.236119877 | SOLVER TARGET | 0.29642927 |
| Probe length | 0.07211 | | |
| Probe radius | 0.000585375 | | |
| **SET lambda start value:** | 0.25 | | |
| **SET alpha start value:** | 5.00E-08 | | |
| **SET H start value:** | 250 | | |
| mc zero | 0.15 | | |

**SET 'solver target' time period** from 60 to 160 seconds.

| conductivity | diffusivity | conductance |
|---|---|---|
| 0.25544 | 5.8596E-08 | 204.019697 |

| x | y | z |
|---|---|---|
| 0.9787033 | 1.17192162 | 1.22537188 |

**SET these to 1 before Solver**

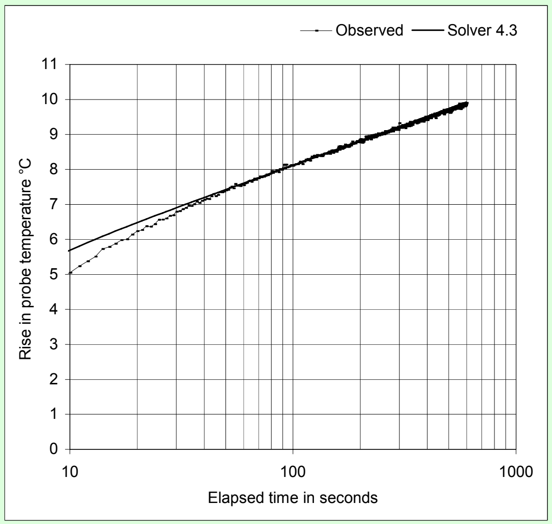
x = lo/l lambda
y = a/ao alpha
z = ho/h conductance

E% tl is <10
Blackwell 2235

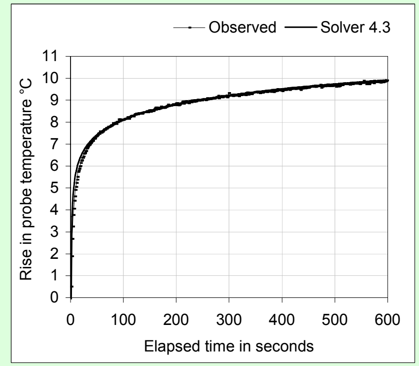
| | | |
|---|---|---|
| **If density** | 608 | $kg/m^3$ |
| specific ht capacity | 7170 | J/kg.K |
| Vol ht cap | 4359 | $kJ/m^3K$ |

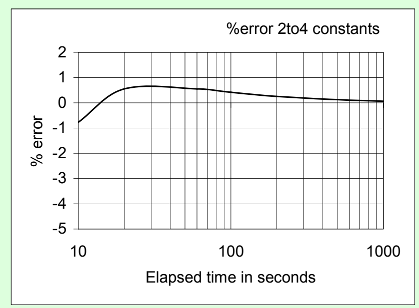
| | |
|---|---|
| constant A | 1.020089432 |
| constant B | 3.32071521 |
| constant C | 1.63E+00 |
| constant D | -4.18E+00 |

| 0 | Expt T1 | Solver T1 | Diff*diff |
|---|---|---|---|
| 1 | 0.5044413 | -0.874668022 | |
| 2 | 1.887450178 | 2.538966816 | |
| 3 | 2.677684122 | 3.695524729 | |
| 4 | 3.243346303 | 4.311562558 | 1.141085968 |
| 5 | 3.763465814 | 4.711300408 | 0.898390417 |
| 6 | 4.051500391 | 5.000727606 | 0.901032305 |
| 7 | 4.413839616 | 5.225179991 | 0.658273205 |
| 8 | 4.61681494 | 5.407517619 | 0.625210726 |
| 9 | 4.911059291 | 5.560635087 | 0.421948716 |
| 10 | 5.049757695 | 5.692423959 | 0.413019927 |
| 11 | 5.231851479 | 5.808023054 | 0.331973684 |
| 12 | 5.374405155 | 5.910945856 | 0.287875924 |
| 13 | 5.507666853 | 6.003690845 | 0.246039801 |
| 14 | 5.726982337 | 6.088093039 | 0.130400939 |
| 15 | 5.786227508 | 6.165537044 | 0.143875724 |
| 16 | 5.876780602 | 6.237091772 | 0.129824139 |
| 17 | 5.976991215 | 6.303598756 | 0.106672486 |
| 18 | 6.000301553 | 6.365731851 | 0.133539303 |
| 19 | 6.136244088 | 6.424038706 | 0.082825742 |
| 20 | 6.234323316 | 6.478970245 | 0.05985212 |
| 21 | 6.267279918 | 6.53090207 | 0.069496639 |
| 22 | 6.373808047 | 6.580150287 | 0.04257712 |
| 23 | 6.365639325 | 6.626983406 | 0.068300728 |
| 24 | 6.435623028 | 6.671631416 | 0.055699959 |
| 25 | 6.557174416 | 6.714292807 | 0.024686189 |
| 26 | 6.565670306 | 6.755140069 | 0.035898791 |
| 27 | 6.595636591 | 6.794324036 | 0.039476701 |
| 28 | 6.671671407 | 6.831977372 | 0.025698002 |
| 29 | 6.690952482 | 6.868217377 | 0.031422843 |
| 30 | 6.793651444 | 6.903148274 | 0.011989556 |




| time | %error 2to4 constants |
|---|---|
| 10 | -0.7702387 |
| 20 | 0.54991642 |
| 60 | 0.55588071 |
| 100 | 0.41694846 |
| 200 | 0.25730515 |
| 500 | 0.12440295 |
| 1000 | 0.06904242 |

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Oak, across the grain

# Results

| Material | Mean $\lambda$ [W/mK] |
|---|---|
| Chestnut along the grain | 0.192 |
| Cob block internal | 0.467 |
| Cob block external | 0.556 |
| Agar immobilised water | 0.613 |
| Cob internal wall base | 0.812 |
| Cob external wall head | 0.861 |
| Cob internal wall head | 0.935 |
| Cob external wall base | 1.139 |

# Conclusions and remarks

A thermal probe allows:

- to quickly measure the heat capacity and / or the insulation properties of materials

- to engineer passive, low carbon heating and cooling building systems

# Conclusions and remarks

- λ: Measurements ± < 5% for standard materials, worse for insulators below 0.05 W/mK. Repeatability better than ± 2%
- VHC: Measurements still not achievable with confidence but provide an indication with reasonable repeatability

# Conclusions and remarks

- Equipment can be calibrated to measure λ and VHC for one probe in one material sample. This does not yet transfer to all materials
- It is not yet possible to isolate the effects on the heating curve of thermal resistance $H$ between the probe and sample

# Conclusions and remarks

- Ongoing modeling effort with Voltra (Physibel) to incrementally identify and allocate the effects of λ, α and $H$ on the heating curve as well as finite boundary conditions such heat losses during experiments, etc

# Conclusions and remarks

Revisiting fundamental theory…

- …where data does not exist
- …where data may not be pertinent

(Thermophysical Properties of Matter gives 338 different values for concrete, 291 for brick – which one are you going to use!?)