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An overview of the Transient Hot Wire and preliminary studies for its implementation

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Abstract. The opportunity to design a new portable system for measuring thermal conductivity in fluids arose from the need to measure the phase state (liquid and/or vapour). As is well known, thermal conductivity varies in relation to the phase state of the fluid. The Transient Hot Wire Method was used to measure thermal conductivity. First, the work includes innovations in the analytical model of heat transfer, progressing over time to contemporary numerical models used in standards. The applications in the bibliography span a wide range, including gases, liquids, and the latest advances in the field of nanofluids. Secondly, the study delves into the transient model of heat exchange, focusing on conduction. The authors used standardized correction equations for the prototype, ensuring accuracy and relevance. Finally, the work includes the design and construction of the transducer. This process begins with a Monte Carlo simulation, predicting the expected results. This simulation helps to define measurement system components based on their performance characteristics and in-depth analysis.

1. Introduction

The practical need for increasingly accurate results has driven the development of knowledge regarding the physical phenomenon related to heat transport. In this work, the authors present a brief history of the evolution over time of research and the reference regulations, starting from1936 when Pfriem, H. [1] addressed both analytical theory and the instrumental practice of measuring thermal conductivity in fluids (gases), contributing to some of the equations used today.
In 1949, E. F.M. Van der Held and F. G. Van Drunen, in [2], reported the hot wire model that is still used today. They wrote the energy balances for the diffusion of heat for the wire and the equation that relates the temperature of the wire to that of the surrounding fluid (to some extent) at a distance r from the wire. In addition to the basic theory, they incorporated considerations on the influence of the thickness of the hot wire, the influence of the diameter of the tube filled with the liquid and the uncertainties due to direct measures such as time and electric current.

In 1981, S.S. Mohammadi et al. [3] proposed a mathematical model with ramp forced corrections for the absolute determination of fluid thermal conductivity using a transient Hot-Wire Technique. The work reports the energy balance equations in the wire and the equation to derive the temperature in the fluid as a function of time and distance from the Hot Wire. Analytical solutions for three heat generation functions (Dirac, step and ramp) are presented, and the exponential integral is presented to define the Truncation error for obtaining the long-time solution. The authors also presented the analysis of approximations to the ideal line-source model.
In 1986, P. G. Knibbe [4] studied the apparatus of thermal conductivity measuring instruments based on the transient line source technique. A theoretical analysis show that the error caused by the end-effect can be kept very small, so that it is not always necessary to correct for this in a practical manner. In the analysis a distinction is made between the conductive and the convective end-effects. The conductive end-effect, which is dominant in the first part of the measurement, is almost constant during this period. The convective end-effect causes an error that increases roughly with the time squared. In 1995, M.L.V Ramires et al. [5] proposed new standard reference data for the thermal conductivity of water based on ITS 90, covering the normal liquid range along the saturation line. These recommendations are based on previously selected as well as on new highly accurate data obtained with transient hot wire instruments, where the wires were coated in the case of water.
In 1995, Xin-Gang Liang [6] discussed the Transient Hot Wire (THW) method, establishing new criteria for error analysis. The analysis includes the influence of dimensions on the accuracy of thermal conductivity measurement and explores the radial and axial effects of the phenomenon.
In 2008, A. G. Ostrogorsky et al. [7] showed how semiconductor melts are low Prandtl number fluids, characterized by high thermal conductivity yielding broad boundary layers and low viscosity that cannot stabilize the buoyancy-driven convection. They measured thermal conductivity by the HWT method during the production of Te-doped InSb crystals, both on the ground and in Microgravity conditions at the International Space Station.
Today, the reference book for the analytical treatment on THW is still that of H.S. Carslaw and J.C. Jaeger [8]. In particular, the authors summarize the analytical theory known in 1959 on heat transmission by conduction. Chapters X and XIII specifically address the linear heat source and the application to theoretical measurement of thermal conductivity.
This paper lays the theoretical foundation for the design of a portable (not inside a cell) and inexpensive instrument for measuring thermal conductivity in fluids. The aim is to achieve a measurement uncertainty compatible with that of benchtop measuring instruments by applying the principles of heat and mass transfer.

2. The principle of the non-stationary method.

2.1. Conceptual and mathematical introduction

The usual methods for measuring the thermal conductivity of a material are based on solving the Fourier differential equation using the stationary method, specifically in cases where the temperature depends only on one coordinate.

$$dq = -\lambda \frac{dT}{dx} dS dt \tag{1}$$

If the material is in a fluid state, this approach introduces challenges related to convection currents. However, mitigating convection currents by employing an extremely thin layer of the fluid makes the measurement of temperature and layer thickness exceptionally difficult.
Referring to Figure 1, imagining the localized heating of a line of a fluid for a very short duration, results in the radial transfer of heat from the axis to the periphery. For example, an electric current can be passed through a thin linear electrical wire drowned in the homogeneous material whose thermal conductivity is to be measured. The consistent generation of heat in the wire induces a cylindrical temperature field

in the material. The temperature rise in the material (indicated by M in Figure 1) depends on the thermal properties of the material. The feasibility of measuring thermal conductivity based on this principle was initially proposed by researchers such as H. S. Carslaw and J. C. Jaeger [8], as well as E. F. M. Van Der Held, J. Hardebol, and J. Kalshoven [2].

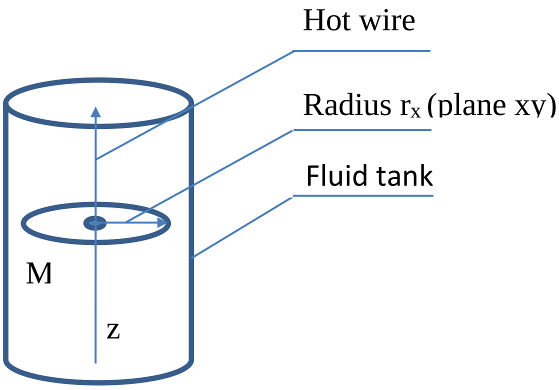

Figure 1. Geometrical scheme of the THW method.

where: M is the material (i.e. water) into the fluid tank, z is the normal to the xy-plane of heat propagation. z is the geometric center of symmetry of the hot wire; r is the radius of the heat propagation in the material (i.e. water).
The approach is based on observing the temperature rise at a given distance "r" from an electrically heated cylindrical wire, which generates a constant heat flow in the liquid. The assumptions are that the wire is infinitely long and negligibly thin. Under these conditions, the Fourier equation and associated boundary conditions apply:

Fourier in radial coordinate system:
$$\frac{\partial T(r,t)}{\partial t} = a\left(\frac{\partial T}{\partial r^2} + \frac{\partial T}{r\partial r}\right) \tag{2}$$

where: a = thermal diffusivity of the liquid (m^2/s); r = distance from the Hot Wire (m); t is the time (s) T is the temperature (K).

Fourier in cartesian coordinate system:
$$\frac{1}{k}\frac{\partial T}{\partial t} = \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) \tag{2'}$$

where: k = 1/a
If we have the continuous line source and we suppose heat to be liberated at the rate $\rho c_P\ \phi(t)$ per unit length of a line parallel to the z-axis and through the point (x', y') in the plane xy in figure 1.
where: ρ is the density (kg/m^3); c_P is the specific heat (W/kgK); ϕ(t) is W/s
If supply of heat starts at t = 0 when the solid is at zero °C, the temperature at time t is:

The solution of Equation 1 is given by

$$\mathrm{T(r,t)} = \frac{1}{4\pi k}\int_0^t \emptyset(t)\cdot e^{\frac{-r^2}{4k(t-t')}}\,\frac{dt'}{(t-t')} \tag{2''}$$

where: $r^2 = (x-x')^2+(y-y')^2$
If ϕ(t) = q, constant, this becomes

$$\mathrm{T(r,t)} = \frac{1}{4\pi k}\int_{\frac{r^2}{4kt}}^{\infty} \frac{e^{-u}}{u}\,du \tag{2'''}$$

$$T(r,t) = -\frac{q_l}{4\pi\lambda} \cdot E_i\left(-\frac{r^2}{4kt}\right) \tag{2''''}$$

$$-E_i(-x) = \int_x^\infty \frac{e^{-u}}{u} du \tag{2'''''}$$

where: E_i = Exponential integral; q_l = linear heat production of the hot wire per unit time and unit length (W/m)
For small values of x:

$$E_i(-x) = -\gamma - \ln x + \frac{x}{1.1!} - \frac{x^2}{2.2!} + \cdots \tag{1}$$

where: γ = Euler's constant: 0.5772

$$\int_0^\infty (z)^{-1}(e)^{-z} dz = -\gamma + \ln\frac{1}{x} + \frac{x}{1.1!} - \frac{x^2}{2.2!} + \cdots \tag{2'}$$

Thus, for large values of t:

$$T(r,t) = \frac{q_l}{4\pi \cdot k} \cdot \left[\ln\left(\frac{4 \cdot k \cdot t}{r^2}\right) - \gamma\right] \tag{3''}$$

If $\rho\ c_p$ = constant

$$T(r,t) = \frac{q_l}{4\pi \cdot \lambda} \cdot \left[\ln\left(\frac{4 \cdot k \cdot t}{r^2}\right) - \gamma\right] = -\frac{q_l}{4\pi \cdot \lambda} \cdot \left[\ln\left(\frac{r^2}{4kt}\right) + \gamma\right] \tag{4'''}$$

by taking the difference in temperature at two times we obtain:

$$T(r,t_1) - T(r,t_2) = \frac{q_l}{4\pi \cdot \lambda} \cdot ln\left(\frac{t_2}{t_2}\right) \tag{4}$$

And obtaining the thermal conductivity from Equation 5:

$$\lambda = \frac{q_l}{4\pi \cdot} \cdot \frac{ln(t_2) - ln(t_1)}{T(r,t_1) - T(r,t_2)} \tag{5}$$

This relation is the base of the non-stationary method of measuring the thermal conductivity of fluids.

2.2. Error causes

Most authors [9 - 14] have cited factors such as the Knudsen effect, the limited cell size, the compressibility and pressure of the fluid, or the loss of heat due to radiation, among other causes of error. According to Healy, Groot and Kestin [15], in the set of experiments conducted by the authors, the "other causes" did not exert a significant influence. For the calculation, three causes of error were considered to calibrate the measurement equipment using the thermal conductivity of distilled water as a benchmark. In particular:

1) *Finite Radius of the Wire:* The finite radius, the finite conductivity, and the heat capacity per unit volume of the platinum wire influence the results. The standard solution for the heat transmission equation assumes a null radius of the wire; thus, in the real case, a small correction must be applied. The correction is not applied directly to the final value of the thermal conductivity but to the value of the final temperature that is reached by the hot wire [16]. The correction value can be calculated by (6):

$$\delta T_{\propto} = r^2 \frac{\left[\left(\rho c_p\right)_w - \rho c_p\right]}{2\lambda t}\Delta T - \frac{q}{4\pi\lambda}\cdot\frac{r^2}{4\lambda t}\cdot\left[2 - \frac{\lambda}{\lambda_w}\right] \tag{6}$$

where: α = radius of the Hot Wire; ρ is the density of fluid (kg/m^3); c_p is the specific heat of the fluid (J/kgK); λ = thermal conductivity of the wire; w is referred to the water

2) *Finite length of the hot wire (end effect):* This error is generated by a nonuniform distribution of temperature in the wire, peaking at the center and decreasing at both edges. Correcting this error is challenging because it is not possible to analytically calculate the temperature distribution as a function of time and space. Therefore, a worst-case scenario correction is employed. Knibbe [4] proposes both a conductive and a convective end-effect correction. In this case, the error correction is calculated directlv for the value of the thermal conductivity via:

$$E = \frac{r}{2L}\sqrt{\left(\frac{\lambda_1}{\lambda}\right)\ln\left(\frac{4at}{r^2\gamma}\right)} \tag{7}$$

where: L is length of the wire; λ_1 is thermal conductivity of the wire; λ is thermal conductivity of fluid

3) *Natural convection*: In the proposed case, the change in the density of the fluid caused by the difference in temperature becomes a complex problem when measuring liquids with diverse kinematic properties. A graphical and numerical method is suggested to appropriately consider the lapse of time for the analysis of thermal conductivity. The analytical model in Equation 4 hypothesized that the values of temperatures are a function only of the thermal properties of the examined fluid and the heat flux generated by the hot wire. By appropriately choosing the start and end points of the curve (T, t), representing the beginning and the apex of the curve obtainable through the concentric cylinder method, it is proposed to obtain the two instants:

$$t > t_{min} = r^2 c_p \rho / 2\lambda \tag{8}$$

where r is the radius of the cylinder (hot wire), λ is the thermal conductivity, ρ is the density, c_p is the specific heat.

3. Apparatus design

3.1. The model to the propagation of uncertainty: Monte Carlo simulation

To define a priori the value of the final uncertainty for thermal conductivity, an uncertainty propagation model was chosen that could reduce the errors of the symbolic calculation as much as possible. The software Matlab was used to implemented manually a Monte Carlo according to ISO/IEC 98-1:2009 and "GUM" [17] using the method of generating 106 samples for each variable. The input quantities of the Monte Carlo simulation are characterized by accuracy and type of distribution summarized in Table 1:

Table 1. Input data of the Monte Carlo simulation

	L (m)	r (m)	I (A)	V (V)	t (s)
U[a]	$1*10^{-5}$	$5*10^{-7}$	$1*10^{-3}$	$380*10^{-6}$	$1*10^{-9}$
D[b]	gaussian	gaussian	rectangular	rectangular	rectangular

[a] Uncertainty.
[b] Distribution.

To the evaluation of Standard Deviation and kurtosis, proceeded according to the block diagram in Figura 2:

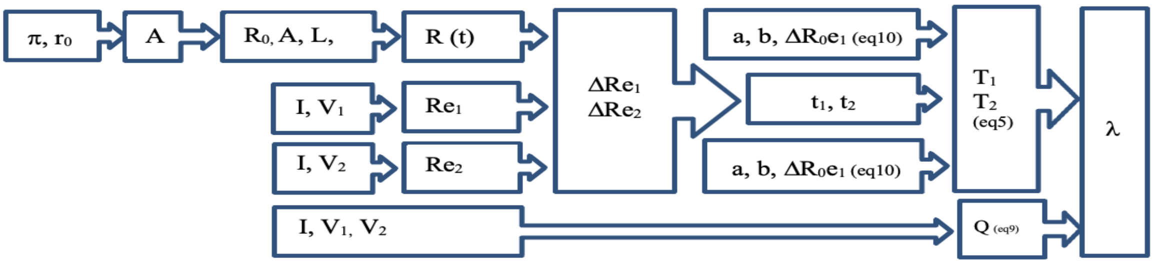

Figure 2. Block diagram to evaluate the uncertainty of the thermal conductivity.

where: r = radius of the hot wire (m); A = wire cross section surface (m^2); t_1, t_2 = times in which the reference quantities are measured (s); Re_1 = electrical resistance of the wire when powered with current I and voltage V_1 (W); Re_2 = electrical resistance of the wire when powered with current I and voltage V_2 (W); $Q_{t1,t2}$ = power average between t_1 and t_2 (W/m).

$$Q(t) = V(t) \cdot I \tag{9}$$

$$R(t) = R_0[1 + aT(t) + bT(t)^2] \tag{10}$$

The equipment was selected (in Table 2) based on their uncertainty characteristics. The uncertainty values of the equipment were used in the uncertainty propagation simulation with Monte Carlo [9] to obtain the design value of the thermal conductivity λ which is about $15*10^{-3}$ (W/mK).

Table 2. Reference of the equipment.

	Accuracy	*Field*
I1[a]	±1(V)	0 - 380 (mV)
I2[b]	10^{-3} [A]	0 – 10 [A]
I3[c]	$5*10^{-7}$ (m)	$25*10^{-3}$ (m)
I4[d]	10^{-5} (m)	$18*10^{-2}$ (m)

[a] DAQ NI USB 6221.
[b] Agilent multimeter model n. 34410.
[c] Micrometre screw gauge.
[d] Calliper gauge Agilent.

The Kurtosis value with Pearson equation of λ is equal to 3.02. The normal distribution is equal to 3.00.

Table 3. Output data of the Monte Carlo simulation.

	A (m^2)	Re (W)	T (°C)	Q (W/m)	k (W/mK)
S. D[a]	$12*10^{-11}$	$55*10^{-5}$	8,28 (1%)	$89*10^{-4}$	$15*10^{-3}$
K[b]	3,01	2,12	3,01	1,98	3,02

[a] Standard Deviation.
[b] Kurtosis.

3.2. Probe designer

The sensor probe (transducer) is designed with the sensor (depicted as a thin line in Figure 3) and the support lying in a plane containing the axis from Figure 1. The sensor wire, constructed from platinum wire (99.99%) with a 38 mm radius, has a minimum length of 33 mm to minimize errors caused by heat conduction to the supports. To reduce the influence of the thermal boundary layer from the supports, the sensors are positioned at least 10 mm away from the walls of the experimental fluid tank (refer to Appendix A). Ensuring maximum verticality during mounting minimizes convection effects on the transducer.
In the described tests, the hot wire is centrally placed between the chamber's center and walls, preventing it from encountering the thermal boundary layer at the wall. The probe's support wire, made of 1.0 mm radius copper wire, is electrically isolated from each other. Copper is chosen for its low temperature coefficient of resistance, crucial for immersion in a bath at a precisely controlled temperature of 0°C, using water in the solid-liquid transition. Throughout the test, the support wires maintain the initial test fluid temperature due to their substantial thermal inertia. Copper's minimal change in resistance over the temperature range prevents measurement errors in length (l) due to resistance variation in the support wires. Bath temperature is measured with a thermometer, accurate to 0.1 K, validated against thermometers calibrated at DIN EN 10204.

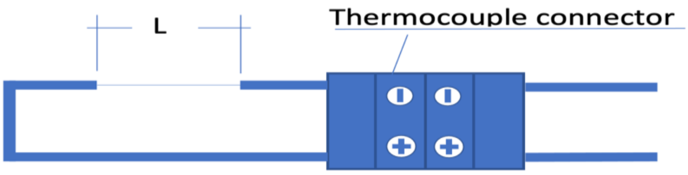

Figure 3. Scheme of the transducer

3.3. Conceptual scheme of connection and Instrumentation

The Hot Wire unit will be including the references equipment and a power supply, DC TENMA 72-10480, with 0-30 [V] DC and 0-3 [A]. The electrical circuit will be performed on power in constant current at 1.0 A.
The conceptual scheme of connection of instrumentation in Figure 4: the DC power supply is connected in series with the ampere-meter (AMP) and with the / Hot wire. The data acquisition system (DAQ) will be connected in parallel to measure the instantaneous variation of the electrical potential (V) at the ends of the platinum hot wire and the data storage (PC).
Next, the current generator (DC) is activated to provide constant current [A]. The values of the voltage at the ends of the transducer (measured by the DAQ board) depend on the temperature (resistance) of the platinum wire (HW).
During the transient state, the voltage acquisition system will be records the changes of the electrical potential at the ends of the platinum wire. The values of the electrical potential at the ends of the

transducer will be recorded the temperature calculate according to the empirical relationship between the resistivity and the temperature, as expressed in Equation 10.
The values presented are the mean value of 30 measurements on 10 experimental procedures, the confidence interval is 95%.

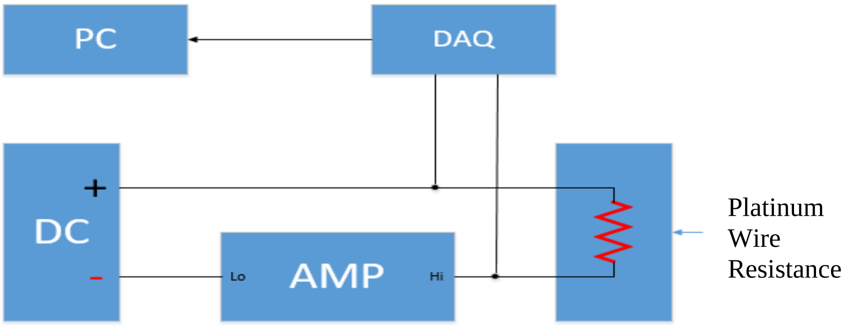

Figure 4. conceptual scheme of connection of instrumentation

4. Conclusions

In this paper, the authors designed a portable transducer based on the thermophysical principles of transient hot wire for measuring thermal conductivity in fluids. They presented the analytical model of heat transfer from the hot wire to the homogeneous fluid around the wire. The causes of systematic errors that most affect the phenomenon of heat and mass transfer in wire/fluid interaction were reported. Through the Monte Carlo simulation proposed in GUM [17], the measuring equipment and DAQ were chosen based on the design value of the uncertainty of thermal conductivity. The next step involves the fabrication and testing of the portable hot-wire transducer.

Acknowledgements

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Appendix

From equation 2'''':

$$\frac{T(r,t)}{\frac{q_l}{4\pi\lambda}} = -E_i\left(-\frac{r^2}{4kt}\right) \quad (A.1)$$

For small values of x, the exponential integral in equation 2'''' can be simplified by truncating its serial development to the first two terms when the r^2 / 4kt argument is much less than 1 and is approximated as,
For x < 0,5

$$Ei(-x) = 0.5772 + lnx - x + \frac{x^2}{4} \text{(Error } 2.132{*}10^{-5} \text{ at x=0.1)} \quad (A.2)$$

For x < 0.1

The exponential integral $Ei(-x) = 0.5772 + lnx$(Error 5.3% at x=0.1) (A.3)
Table A.1 respectively.
In Figure A.1 the Exponential Integral exact (full lines) and two-term approximation (dashed line with squares, equation A.4) and four term approximation (dashed line triangles, equation A.2).

$$\frac{T(r,t)}{\frac{Q}{4\pi k}} = -\left[-0{,}5772 + \ln\left(\frac{r^2}{4a_t t}\right) - \frac{r^2}{4a_t t} + \frac{1}{4}\left(\frac{r^2}{4a_t t}\right)^2\right] \quad \text{(A.4)}$$

Note that r < 0,5, correspond to Ei > 0,56, i.e. the high temperature region closes to the continuous line source, which is of interested. One is usually not interested in the low temperature region, away from the source (large r and low t),

$$\frac{r^2}{4a_t t} > 0{,}5$$

Therefore, equation A.4 can be used in most practical situations.
For values of r>0.5, the exponential integral is given as chart and a table A.1.

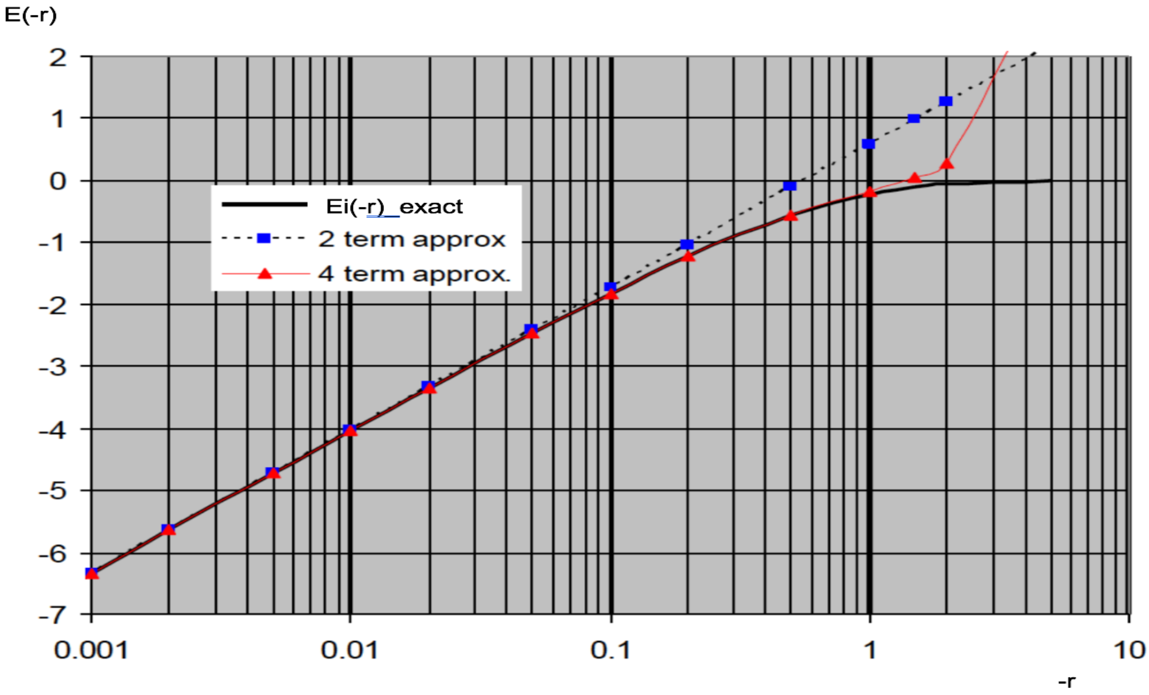

Figure A.1. Exponential Integral approximation.

From the equation 9 at t=0.5 s, the four-term approximation, equation A.4 becomes inaccurate for>0.7 mm.
The authors propose figure A.2 in a pure heat conduction case.

Table A.1. Ei approximation function of -r

-r (mm)	-Ei(-r)	_(0.3)	_(0.4)	Error_(0.3)	Error_(0.4)
0.01	4.037930	4.037945	4.027970	-3.86559E-06	0.002466460
0.02	3.354708	3.354723	3.334823	-4.53763E-06	0.005927425
0.05	2.467898	2.467907	2.418532	-3.55953E-06	0.020003341
0.1	1.822924	1.822885	1.725385	2.13201E-05	0.053506821
0.2	1.222651	1.222238	1.032238	0.000337489	0.155737576
0.5	0.559774	0.553447	0.115947	0.011301738	0.792867721
0.8	0.310597	0.285944		0.079373145	
1	0.219384	0.172800		0.212339771	
1.2	0.158408	0.080478		0.491956080	
1.5	0.100020				
2	0.048901				
3	0.013048				
4	0.003779				
5	0.001148				
8	0.000115				
10	0.000004				

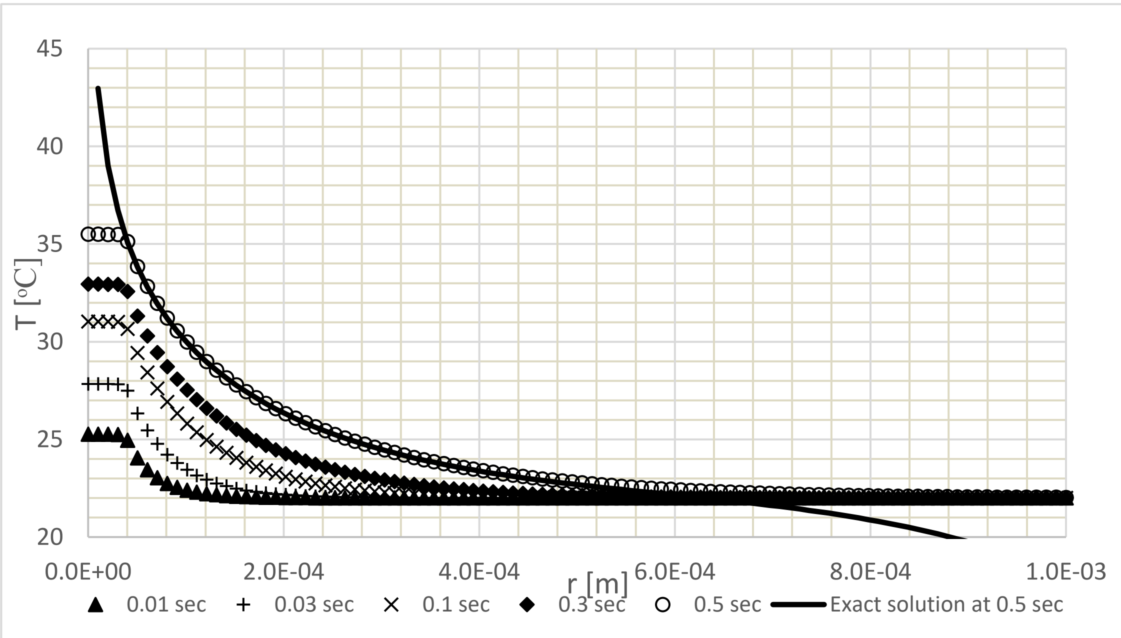

Figure A.2. Radial temperature distribution for the case of pure heat conduction

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