TRANSVERSE HEAT TRANSFER COEFFICIENT IN THE ITER TF CICCs

Part II. Analysis of transient temperature responses observed during heat slug propagation tests

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CHATS-AS , Cambridge, 9-11 Oct. 2013

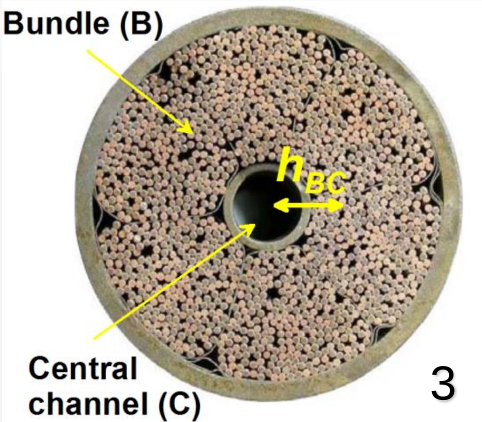
Outline

- Motivation
- Experimental setup and conductor characteristics
- Evaluation of the heat transfer coefficient
  - – Method proposed in [1] and its modifications
  - – Method proposed in [2]
- Results
- Summary and conclusions

[1] Bottura L, Bruzzone P, Marinucci C, Stepanov B. Cryogenics 2006; 46: 597–605
[2] Renard B, Martinez A, Duchateau J-L, Tadrist L. Cryogenics 2006; 46: 530–40.

Motivation (I)

- The simple „meso-scale" representation of a CICC with a central channel is a 1-D dual channel model, which requires constitutive relations, i.e. friction factors f_B and f_C, and transverse heat transfer coefficient h_{BC} .
- Reliable predictive correlation for h_{BC} does not exist.
- The results of theoretical efforts [3-5] are neither comprehensive nor free of contradictions.
- The database of h_{BC} data obtained by interpretation of experimental data using simple models [1,2,6,7] is very modest.



[3] Long AE. M. Sc. Thesis, MIT, Cambridge-MA, 1995.
[4] Nicollet S, Ciazynski D, *et al*. Proceedings of ICEC 20, Beijing, China, 2005, 589-92.
[5] Zanino R, Giors S, Savoldi Richard L. Cryogenics 2010; 50: 158-166.
[6] Renard B, Duchateau J-L, Rousset B, Tadrist L. Cryogenics 2006; 46: 629–42.
[7] Marinucci C, Bottura L, Bruzzone P, Stepanov B. Cryogenics 2007; 47: 563–76.

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Motivation (II)

- Two thermal-hydraulic test campaings of two full-size ITER TF conductors were carried out in SULTAN at EPFL-CRPP in 2008 and 2009 [8,9] .
- Unique instrumentation was used:
  - large number of thermometers and heaters,
  - ‘intrusive’ instrumentation mounted inside the cable space.
- Main goal of these experiments was to study the occurence of the flow – reversal effect, but …
  Why not to use the collected data for other analyses?

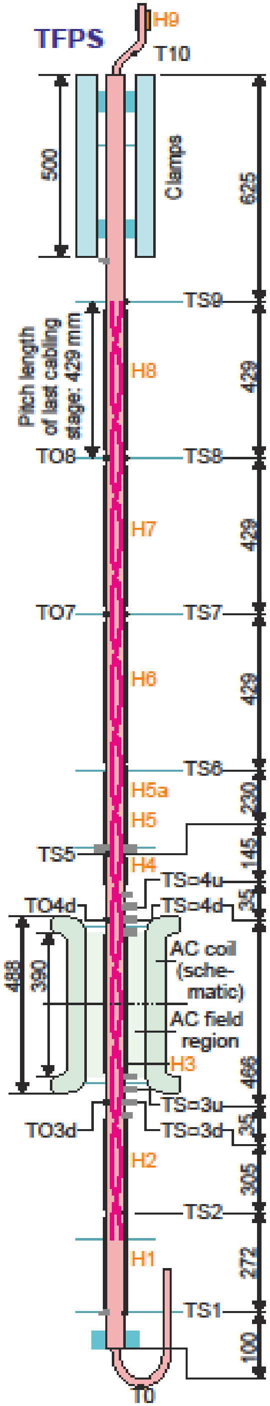
A systematic investigation of h_{BC} in the ITER TF CICCs can be performed using different approaches [1,2,6].

[8] Herzog R, Lewandowska M, Bagnasco *et al* . IEEE Trans Appl Supercond 2009; 19: 1488-91.
[9] Herzog R, Lewandowska M, Calvi M, Bessette D. J Phys: Conf Ser 2010; 234: 032022 (8 pp)

Motivation (III)

- In Part I [10] we derived h_{BC} values using method based on analysis of steady state temperature profiles along the sample resulting from the local annular heating [6] .
- In the present study the results of the heat – slug propagation tests will be interpreted using two different approaches proposed in [1] and [2].

[10] Lewandowska M, Herzog R. Cryogenics 2011; 51: 598-608.



EXPERIMENTAL (I) [9]

CONDUCTOR:

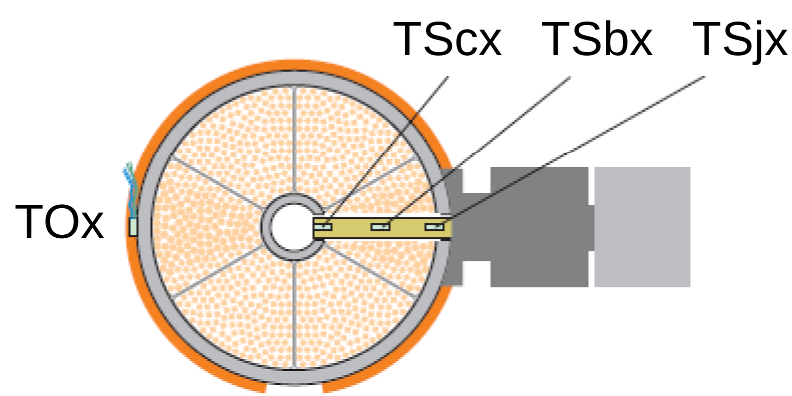
- ALSTOM B TF Performance Sample (**TFPS**)

Conductor parameter (unit)	Symbol	Value
Central spiral diameter (mm)	D_{in}/D_{out}	8/10
Spiral gap fraction (-)	*perf*	0.30
Bundle He cross section (mm²)	A_B	384.8
Central channel He cross section (mm²)	A_C	58.7
Bundle /channel wetted perimeter (mm)	p_{BC}	28.3

$$A_C = \pi[(1-perf)D_{in}^2 + perf D_{out}^2]/4$$ [2]

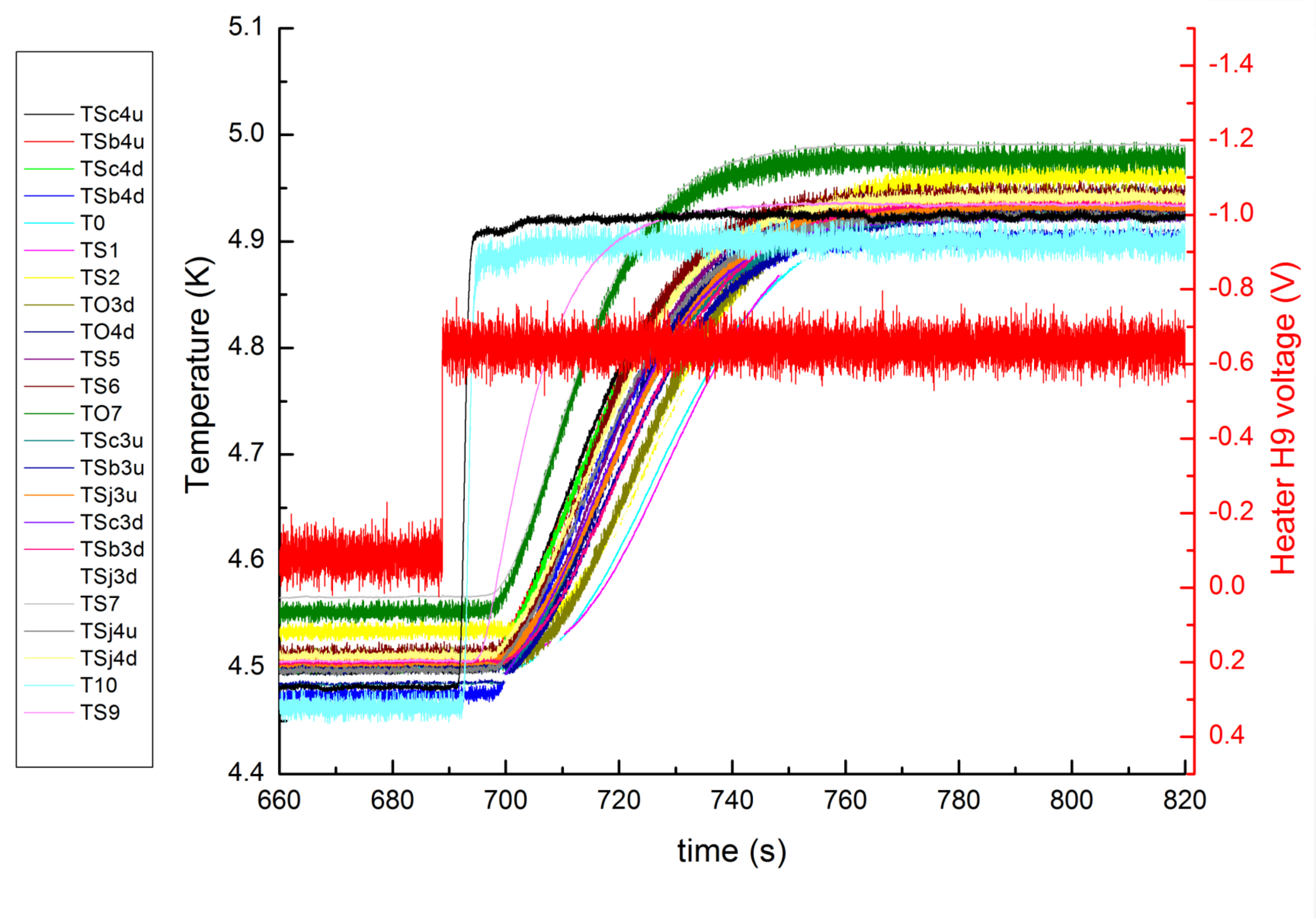
TEST CONDITIONS:

- Supercritical He at 4.5 K and 10 bar
- downward flow direction
- $\dot{m}$ = 4 to 10 g/s
- 4 consecutive pulses of 0.45 K were generated by heater H9 at each mass flow rate



T-sensors 3d, 3u, 4d and 4u

Experimental (II)



Typical example of raw data set

Method proposed in [1]

Mathematical model (I)

$$
\begin{cases}
\dot{m}_C C_p \dfrac{\partial T_C}{\partial t} + \rho C_p v_C \dfrac{\partial T_C}{\partial x} = \dfrac{p_{BC} h_{BC}}{A_C}\left(T_B - T_C\right) \\
\dot{m}_B C_p \dfrac{\partial T_B}{\partial t} + \rho C_p v_B \dfrac{\partial T_B}{\partial t} = \dfrac{p_{BC} h_{BC}}{A_B}\left(T_C - T_B\right)
\end{cases}
$$

$$
\frac{\partial T}{\partial t} + v\frac{\partial T}{\partial x} - k\frac{\partial^2 T}{\partial x^2} = 0
$$

Where:

$T(x,t) = \left[T_C(x,t) + T_B(x,t)\right]/2$ - average temperature field in a CICC

$v = \dfrac{A_C v_C + A_B v_B}{A_C + A_B}$ - average flow velocity

$k = \dfrac{A_C^2 A_B^2}{(A_C + A_B)^3}\left(\dfrac{\rho C_p}{p_{BC} h_{BC}}\right)(v_C - v_B)^2$ - diffusion coefficient

Method proposed in [1]
Mathematical model (II)

$$\frac{\partial T}{\partial t} + v\frac{\partial T}{\partial x} - k\frac{\partial^2 T}{\partial x^2} = 0$$

$$\xi = x - vt$$

$$\frac{\partial T}{\partial t} - k\frac{\partial^2 T}{\partial \xi^2} = 0$$

$T(\xi < 0,0) = T_1 \quad T(\xi = 0,0) = (T_0 + T_1)/2 \quad T(\xi > 0,0) = T_0$ - initial conditions

$T(-\infty, t) = T_1 \qquad T(+\infty, t) = T_0$ - boundary conditions

$$T(\xi, t) = T_0 + \frac{1}{2}(T_1 - T_0)\mathrm{erfc}\left(\frac{\xi}{2\sqrt{kt}}\right)$$ - solution in moving frame

$$T(x, t) = T_0 + \frac{1}{2}(T_1 - T_0)\mathrm{erfc}\left(\frac{x - vt}{2\sqrt{kt}}\right)$$ - solution in laboratory frame

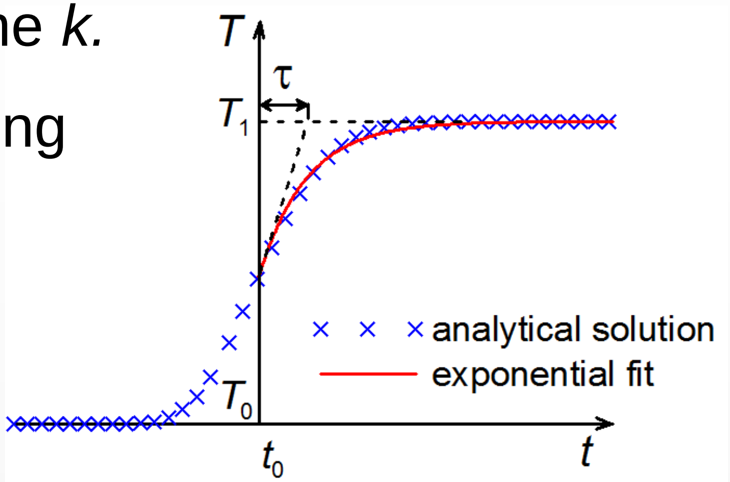
The analytical solution could be matched to temperature response of *T*-sensors → ***k***

In practice it is impossible to obtain in this way reproducible results for all *T*-sensors

Method proposed in [1]

Mathematical model (III)

- The characteristic time constant τ of the temperature rise at half height is a useful tool to determine *k*.



- Time constant τ is defined by matching an exponential model:

$$T(t,t_0) = T_1 - \left(\frac{T_1 - T_0}{2}\right)\exp\left(\frac{t_0 - t}{\tau}\right)$$

to the analytical solution,

t_0 is the time in which the temperature at the location of observation *x* reaches the value $(T_0+T_1)/2$.

- By repeating matching at various values of *k*, *v* and *x* the scaling law for τ was obtained in [1]:

$$\tau \approx \sqrt{\pi}\sqrt{\frac{kx}{v^3}}$$

Method proposed in [1]

Method of h_{BC} evaluation

By fitting the exponential model to the temperature responses of thermometers located along the sample, a set of experimental values of the characteristic time $\{\tau_{exp}\}$ can be obtained.

$\{\tau_{exp}\}$

↓ scaling law

$\{k_{exp}\}$

↓ statistical analysis

k_{mean} , u(k)

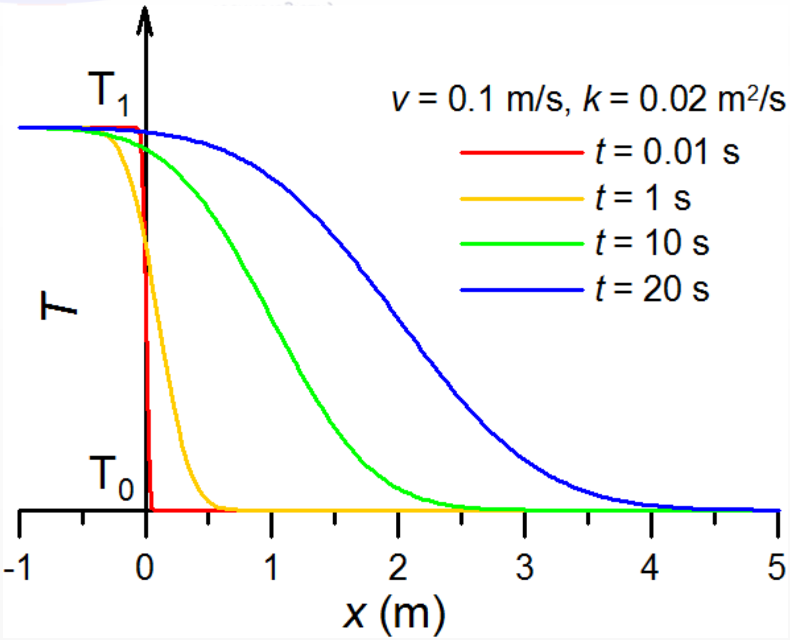
↓ definition of k

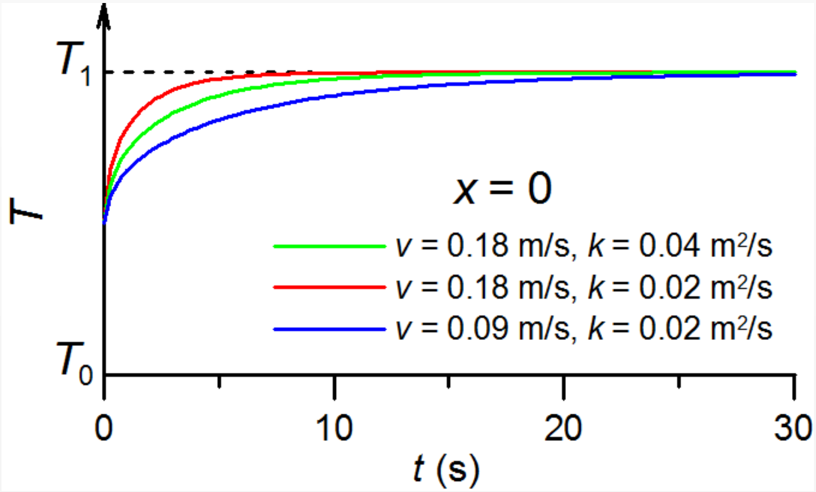
h_{BC} , u(h_{BC})

Method fast and convenient in practical use

This method was applied in [1] to determine h_{BC} in $PFIS_W$ and $PFIS_{NW}$ CICCs. The same experimental data were analysed in [2] using another method.

Method proposed in [1]
Problem with the model (I)





- The model formulated in [1] considers time evolution of the rectangular temperature step at x=0 imposed as the initial condition.
- According to the analytical solution presented in [1] temperature at $x = 0$ (corresponding to the sample inlet) varies with time:

$$T(x=0,t) = T_0 + \frac{1}{2}(T_1 - T_0)erfc\left(\frac{-v}{2}\sqrt{\frac{t}{k}}\right)$$

- As a result of the mathematical model adopted in [1] a smeared step of the helium inlet temperature occurs.
- The case considered in [1] is not equivalent to the case of rectangular step change of the inlet temperature.

Method proposed in [1]

Problem with the model (II)

In the ideal case the temperature step entering the sample should be rectangular, however …

- heat exchange between the heater and helium is not instantaneous,
- heat pulse travels a distance between the heater and the sample inlet, which results in some diffusion,
- helium flow may be disturbed at the sample inlet or due to the presence of joints (if any).

The actual time dependence of the inlet temperature cannot be verified - thermometers have not been installed at the sample inlet ☹

Is the scalling law for τ (and the resulting h_{BC}) affected by the way of the model formulation ???

Method modifications

Case 1: rectangular *T* - step imposed at the boundary *x* = 0

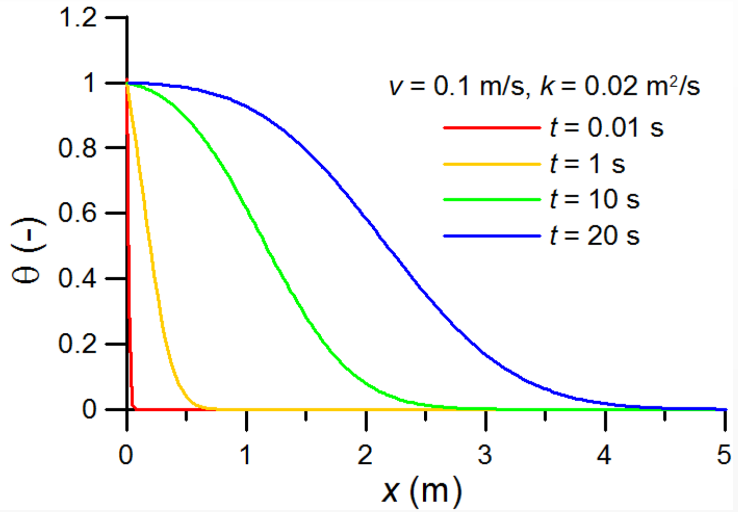
$$\theta = \frac{T - T_0}{T_1 - T_0}$$ - dimensionless temperature

$$\frac{\partial \theta}{\partial t} + v\frac{\partial \theta}{\partial x} - k\frac{\partial^2 \theta}{\partial x^2} = 0$$

$$\theta(x,0) = 0$$ - initial condition

$$\theta(0,t) = \begin{cases} 0 & \text{for } t \le 0 \\ 1 & \text{for } t > 0 \end{cases}$$ - boundary conditions

$$\theta(\infty, t) = 0$$



$$\theta(x,t) = \frac{1}{2}\left[\operatorname{erfc}\left(\frac{x - vt}{2\sqrt{kt}}\right) + \exp\left(\frac{vx}{k}\right)\operatorname{erfc}\left(\frac{x + vt}{2\sqrt{kt}}\right)\right]$$ - analytical solution

$$\tau \approx \frac{4}{3}\sqrt{\frac{kx}{v^3}}$$

- scaling law providing h_{BC} values $(16/9\pi) \approx$ **1.8 times smaller** than the scaling law obtained in [1]

A very dissatisfactory disambiguity ☹

Method modifications

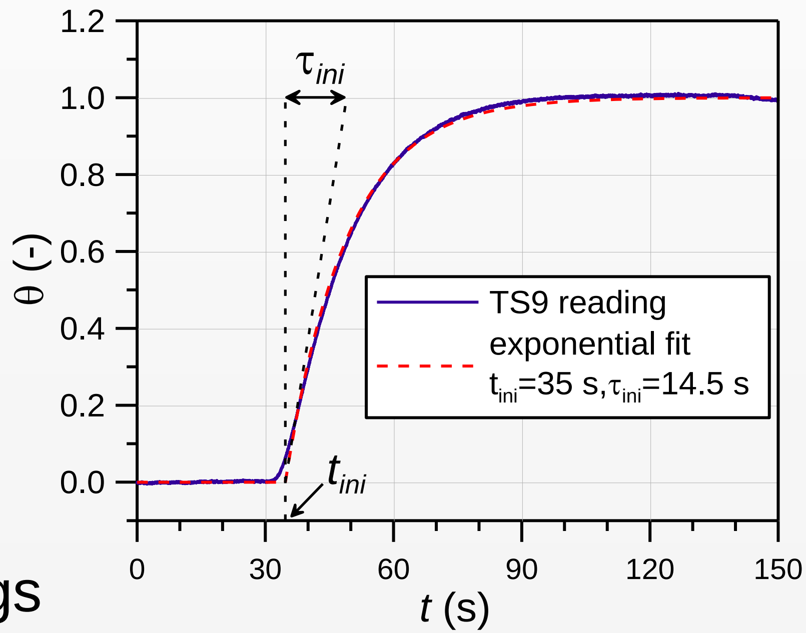
Case 2: TS9 reading used as the boundary condition (I)

- We chose the origin of the *x* coordinate at the location of the thermometer closest to the sample inlet (TS9 in our case).
- Reading of TS9-sensor for each pulse is approximated by an exponential model

$$\theta(0,t) = \begin{cases} 0 & \text{for } t \le t_{ini} \\ 1 - \exp\left(\dfrac{t_{ini} - t}{\tau_{ini}}\right) & \text{for } t > t_{ini} \end{cases}$$

to be used as the boundary condition at $x = 0$.

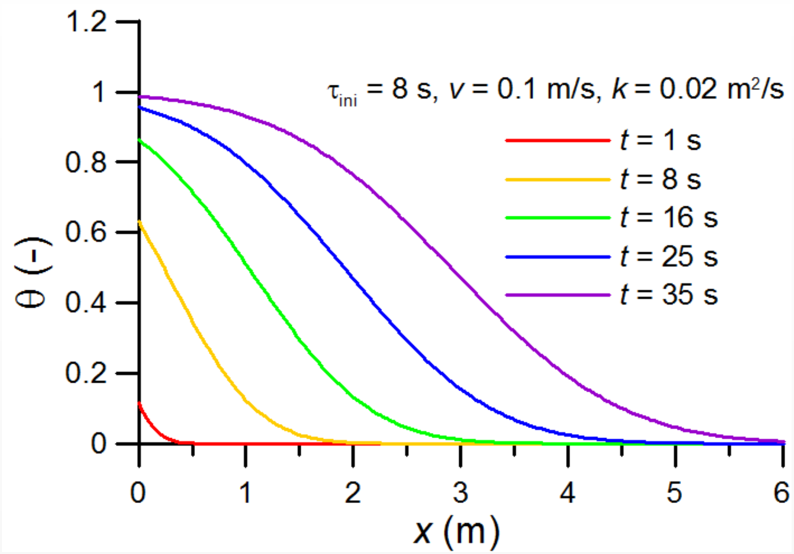
- Least square fitting is used to match the exponential model to TS9 readings for each pulse → t_{ini} and τ_{ini} .



Method modifications

Case 2: *TS9* reading used as the boundary condition (II)

$$\begin{cases} \dfrac{\partial\theta}{\partial t} + v\dfrac{\partial\theta}{\partial x} - k\dfrac{\partial^2\theta}{\partial x^2} = 0 \\ \theta(x,0) = 0 \\ \theta(0,t) = \begin{cases} 0 & \text{for } t \le 0 \\ 1 - \exp\left(-t/\tau_{ini}\right) & \text{for } t > 0 \end{cases} \\ \theta(\infty,t) = 0 \end{cases}$$



$$\theta(x,t) = \theta_1(x,t) - \theta_2(x,t)$$

$$\theta_1(x,t) = \frac{1}{2}\left[\operatorname{erfc}\left(\frac{x - vt}{2\sqrt{kt}}\right) + \exp\left(\frac{vx}{k}\right)\operatorname{erfc}\left(\frac{x + vt}{2\sqrt{kt}}\right)\right]$$

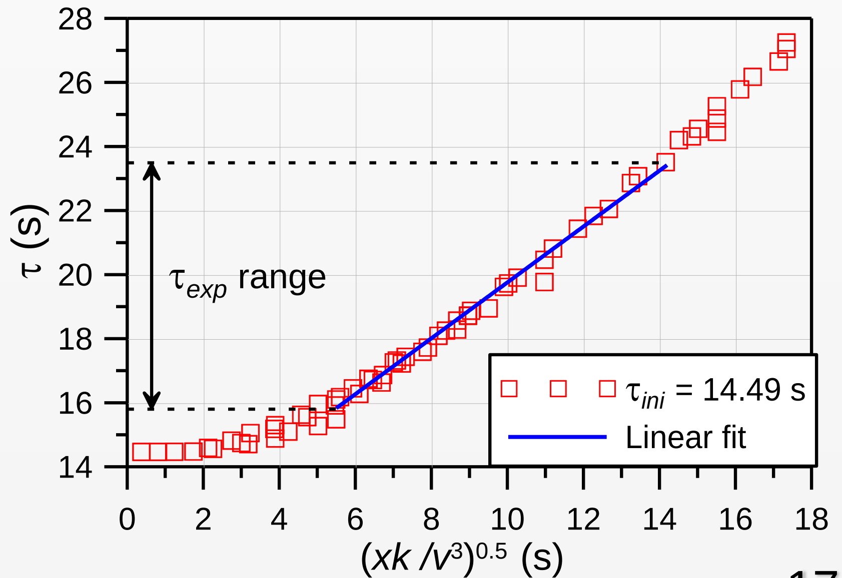
$$\theta_2(x,t) = \frac{1}{2}\exp\left(\frac{-t}{\tau_{ini}}\right)\exp\left(\frac{vx}{2k}\right)\frac{x}{\sqrt{\pi k}}\int_0^t \xi^{-3/2}\exp\left[\xi\left(\frac{1}{\tau_{ini}} - \frac{v^2}{4k}\right) - \frac{x^2}{4k\xi}\right]d\xi$$

Method modifications

Case 2: *TS9* reading used as the boundary condition (III)

- We did not manage to formulate a universal scaling law, which is a disadvantage of this approach.
- In principle a separate scaling equations should be obtained for each τ_{ini} value (i.e. for each considered pulse). However, for similar values of τ_{ini} we used their average.
- Least square fitting was used to obtain scaling equations in the linear form:

$$\tau \approx a\sqrt{kx/v^3} + b$$



Method proposed in [1] and its modifications

Uncertainties evaluation

$\{\tau_{exp}\}$

↓

$\{k_{exp}\}$

↓

k_{mean}, u(k)

↓

h_{BC}, u(h_{BC})

$$h_{BC} = \frac{1}{k}\frac{A_C^2 A_B^2}{(A_C + A_B)^3}\left(\frac{\rho C_p}{p_{BC}}\right)\left[v_C\left(1+\frac{A_C}{A_B}\right)-\frac{\dot{m}}{A_B\rho}\right]^2$$

$$u(k_{mean}) = \sqrt{\frac{\sum_{i=1}^{n}\left(k_{\exp_i} - k_{mean}\right)^2}{n(n-1)}}$$

Relative uncertainties:

$u(\dot{m})/\dot{m} = 5\%$

$u(v_C)/v_C = 25/5\,\%$ (upper/lower bound) [9]

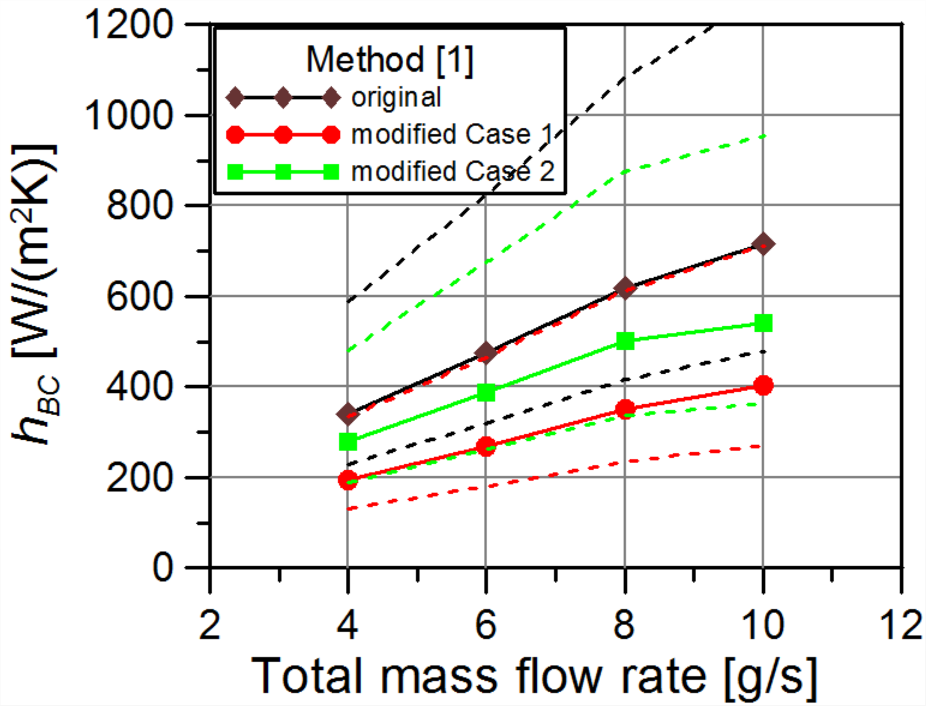
$u(A_C)/A_C = 15\,\%$ (lower), due to different definitions

$$u(h_{BC}) = \sqrt{\left(\frac{\partial h_{BC}}{\partial v_C}\right)^2 u^2(v_C) + \left(\frac{\partial h_{BC}}{\partial A_C}\right)^2 u^2(A_C) + \left(\frac{\partial h_{BC}}{\partial \dot{m}}\right)^2 u^2(\dot{m}) + \left(\frac{\partial h_{BC}}{\partial k}\right)^2 u^2(k)}$$

The resulting uncertainties of h_{BC} are large ☹ (up to 70% for the upper bound)

Method proposed in [1] and its modifications

Results



- All methods are very sensitive to small changes of the v_C and A_C values used in the evaluation of h_{BC} (v_C is the most critical).
- Accurate knowledge of the flow partition in a cable is necessary to obtain reliable h_{BC} values, which seems challenging with the existing methods.

Method proposed in [2]

Mathematical model

$$\begin{cases} \dot m_C C_p \frac{\partial T_C}{\partial t} + \rho C_p v_C \frac{\partial T_C}{\partial x} = \frac{p_{BC} h_{BC}}{A_C}(T_B - T_C) \\ \dot m_B C_p \frac{\partial T_B}{\partial t} + \rho C_p v_B \frac{\partial T_B}{\partial t} = \frac{p_{BC} h_{BC}}{A_B}(T_C - T_B) \\ T_B(x, t=0) = T_C(x, t=0) = T_0 \\ T_B(x=0, t) = T_C(x=0, t) = \begin{cases} T_0 & \text{for } t < 0 \\ T_1 & \text{for } t \geq 0 \end{cases} \end{cases}$$

$$\theta_B(x,t) = \begin{cases} 0 & \text{for } t \leq x/v_C \\ 2\alpha \exp(-\alpha) \int_0^\delta \beta \exp(-\alpha\beta^2) \mathrm{I}_0(2\alpha\beta) \mathrm{d}\beta & \text{for } x/v_C < t < x/v_B \\ 1 & \text{for } t \geq x/v_B \end{cases}$$

$$\alpha(x,t) = \frac{h_{BC} p_{BC}}{\rho A_i C_p} \cdot \frac{x - v_B t}{v_C - v_B} \qquad \delta(x,t) = \sqrt{\frac{(v_C t - x) A_C}{(x - v_B t) A_B}}$$

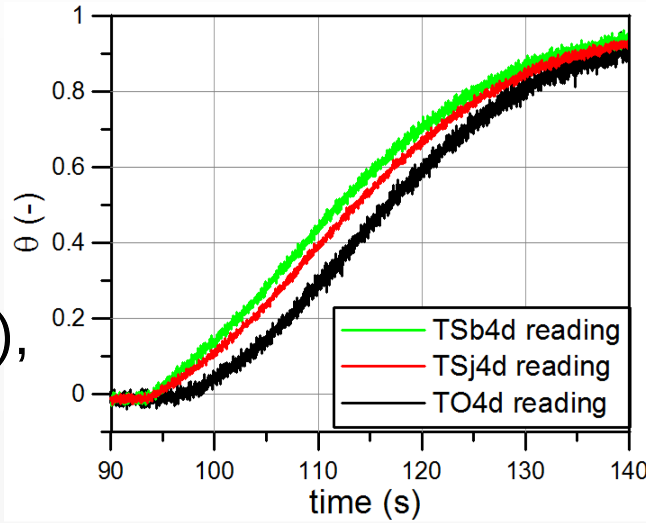
Following [1] we assume that readings of TSx, TOx, TSbx and TSjx sensors can be approximated by the analytical solution θ_B

Method proposed in [2]

Starting delay

Time at which the temperature rise is registered by the *T*-sensor located at a distance *x* depends on:

- the time t_0 at which the heater is switched on,
- the time delay Δt_h, after which the heat pulse reaches the sample inlet,
- the time delay related to the duration of heat transfer in the radial direction (difficult to estimate, but visible in our data),



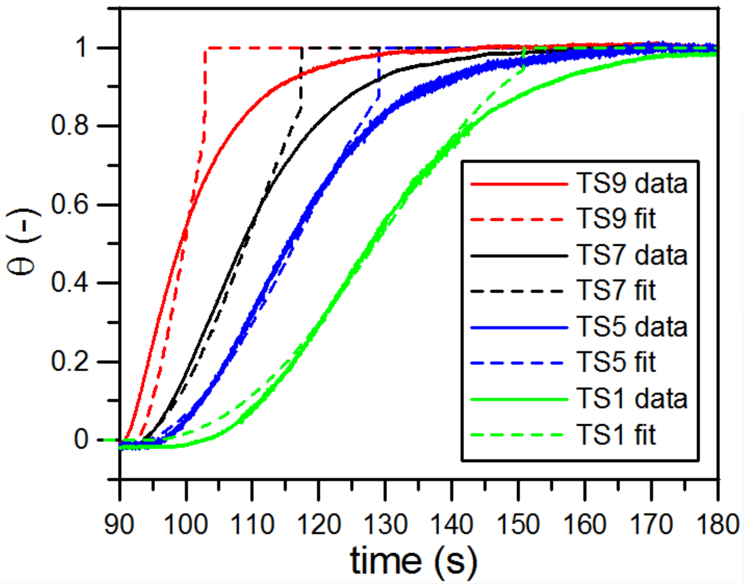
- the time during which the heat pulse travels a distance *x* within the sample (taken into account in the analytical solution).

The first three effects are lumped together into one parameter called „***starting delay***" [2]. Its value can be determined by matching the solution to experimental data.

Method proposed in [2]

Fitting

- We used the least square fitting procedure with the two free parameters h_{BC} and t_{del}.
- A characteristic feature of the analytical solutions is a sharp temperature front at $\boldsymbol{t = t_{del} + x/v_B}$, where *x* is the sensor position.
- Such a temperature jump is not observed in *T*-sensors' readings.

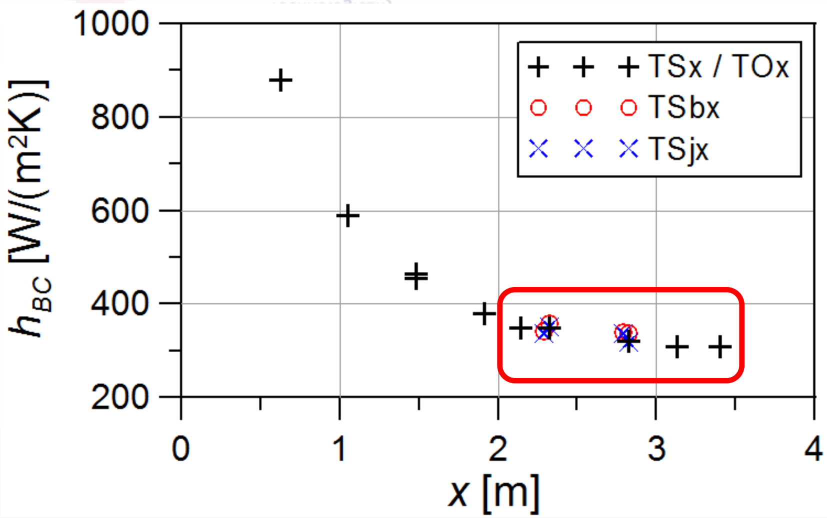


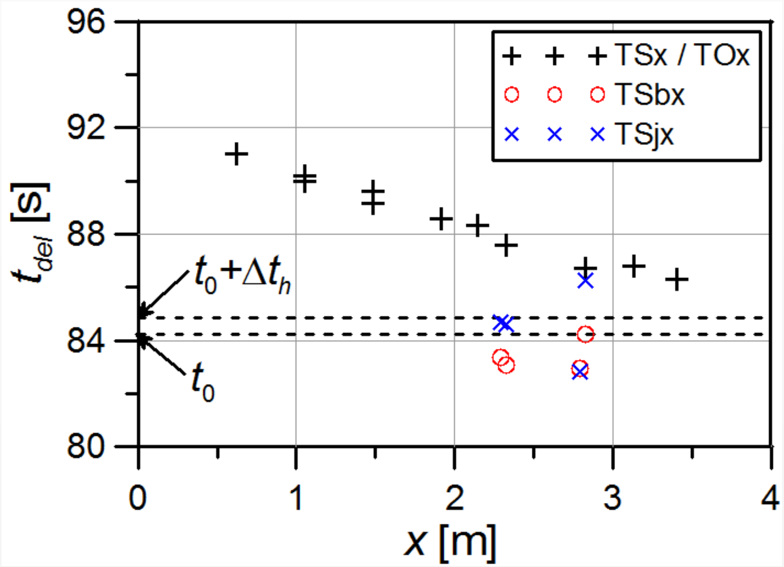
- The smaller is *x* the higher is the temperature front and the poorer the agreement between the fits and the data.

For small *x* parameters h_{BC} and t_{del} , obtained from fitting, are pushed towards higher values.

Method proposed in [2]

Observed trends





- For the further statistical analysis we used only h_{BC} values obtained for thermometers at x > 2 m, for which the dependence on *x* is weak.
- The h_{BC} values for the sensors TOx, TSjx and TSbx located at the same distance are consistent ☺
- The dependence of the starting delay on *x* cannot be explained by the presence of joints.
- The values of t_{del} for thermometers mounted inside the cable are very small (**some are smaller than t_0!**).
- **Parameter t_{del} does not have a clear physical interpretation??**

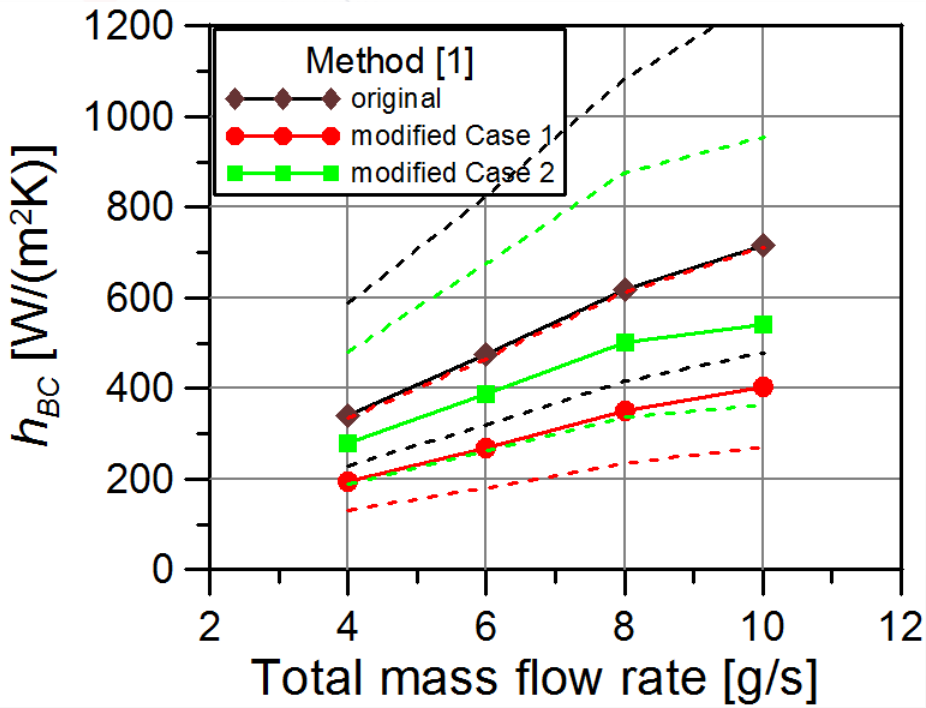
Method proposed in [2]

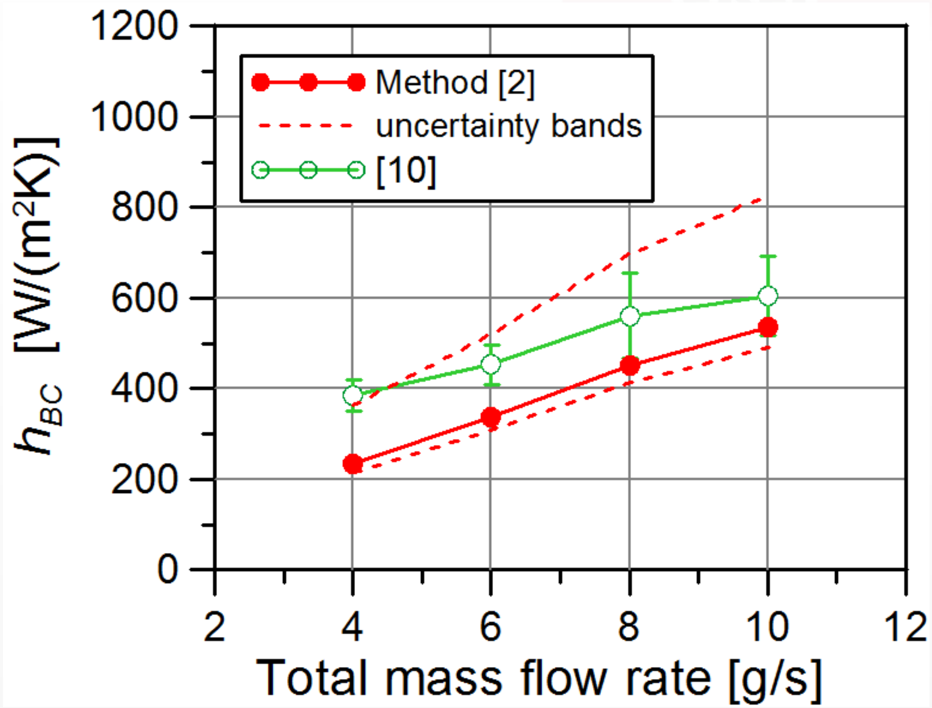
Uncertainties evaluation

- The uncertainties of h_{BC} resulting from the fitting procedure and standard deviations of the mean are very small (of about 2%).
- To assess the contributions of the uncertainties of v_C, A_C and $\dot{m}$ used in the calculations to the uncertainty of h_{BC}, we performed a sensitivity analysis.
- We increased (or decreased) the value of one of the parameters v_C, A_C or $\dot{m}$ by the value of the respective error bar and repeated the fitting procedure for several selected thermometers. Then we estimated the respective relative change of the h_{BC} value.
- All these contributions were lumped together resulting in an upper band of the h_{BC} uncertainty of 54% and lower one of 8.4%.
- The values of t_{del} were much more stable than h_{BC} with respect to the changes of parameters v_C, A_C and $\dot{m}$.

The surprisingly small values of t_{del} obtained for the sensors mounted in the cable space cannot result from the inaccurately measured v_C used in the calculations.

Results





The h_{BC} values obtained in [1] for the $PFIS_W$ and $PFIS_{NW}$ conductors were systematically smaller (about 30%) than those in [2].

Here we see the opposite trend.

Different methods of v_C evaluation and different A_C definitions used in [1] and [2] can be the possible reason of inconsistent results.

Summary and Conclusions

- We derived the h_{BC} values for the final-design ITER TF conductor from the measurements of a heat slug propagation experiment.
- Two different models proposed in [1] and [2] were used for interpretation of experimental data.
- To the former we added 2 modifications and assessed their impact on the results.
- Results obtained with both methods are sensitive to uncertainties of v_C, A_C and $\dot{m}$ values used in the calculations (v_C is the most critical). The resulting uncertainties of h_{BC} are particularly large (up to 70%) with the method proposed in [1] and its modifications.
- The original method [1] and its 1st modification are rapid in practical use, but they can provide the approximate range in which h_{BC} value should fall.
- The 2nd modification proposed by us does not involve any unverified assumptions about the helium inlet temperature, but requires more efforts, since no universal scaling equation for τ was formulated.
- Method proposed [2] is based on unrealistic assumption that the temperature step is rectangular which affects the results → modification could be proposed ?
- Method based on analysis of steady state temperature profiles resulting from annular heating [6] seems more accurate.

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Thank you for your attention

Question Time