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HEAT AND MASS TRANSFER TO PARTICLES IN FLUIDIZED BED

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CORRELATIONS: SINGLE-PHASE FLOW

Relationships for single spherical particles in single-phase flow have been determined by Frössling (1938), Ranz-Marshall (1952) , Rowe (1965)

$$Nu_a=2+0.69Re_a^{0.5}Pr^{0.33}$$

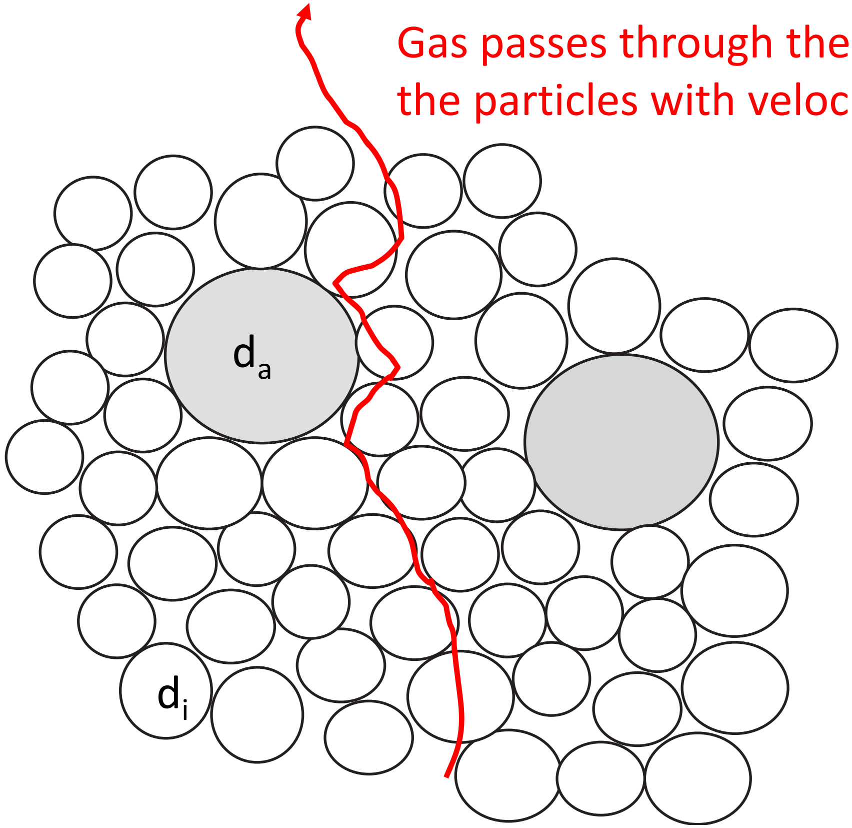
$$Sh_a=2+0.69Re_a^{0.5}Sc^{0.33}$$

Gas conduction and gas convection terms, related to the particle diameter d_a, are analogous for heat and mass transfer in this case.

Contribution from radiation has to be added in the heat transfer case.

Heat transfer	$Nu_a=hd_a/k$	$Pr=\mu c_p/k$
Mass transfer	$Sh_a=\beta d_a/D$	$Sc=\nu/D$

HEAT AND MASS TRANSFER BETWEEN THE GAS AND ACTIVE PARTICLES IN THE BED

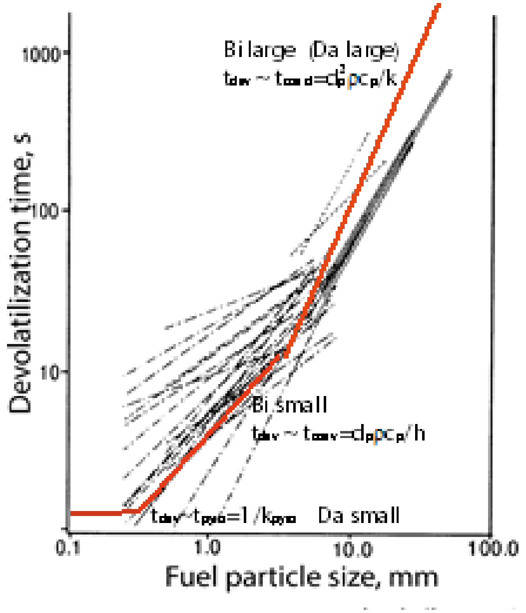


Gas passes through the space between the particles with velocity u_{mf}/ε

Two large active particles surrounded by smaller inert particles in a bed with fluidization velocity u.

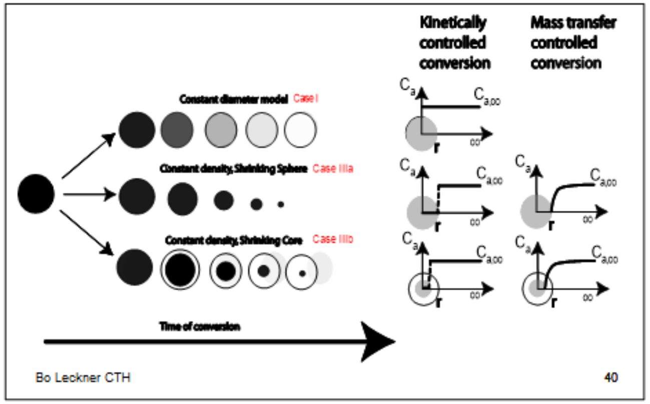
APPLICATIONS

Various chemical engineering processes in fluidized bed, e.g. in fuel conversion



Drying and pyrolysis of fuel particles

REGIMES OF CHAR CONVERSION



Combustion of char

CORRELATIONS: FLUIDIZED BED

There are many correlations giving different results having a similar structure (Shown for heat transfer (Nu) but analogous for mass transfer (Sh))

$$Nu_a = const + const(\mathrm{Re}_{a,mf} / \varepsilon_{mf})^n \,\mathrm{Pr}^{0.33}$$

where $Nu_a = h_c d_a / k_g$ $\quad \mathrm{Re}_{a,mf} = u_{mf} d_a \rho_g / \mu$

or

$$Nu_i = const \; Ar^n (d_a / d_i)^m$$

where $Nu_i = h_c d_i / k_g$ and $Ar = d_i^3 g \rho_g (\rho_s - \rho_g) / \mu^2$

Transformations

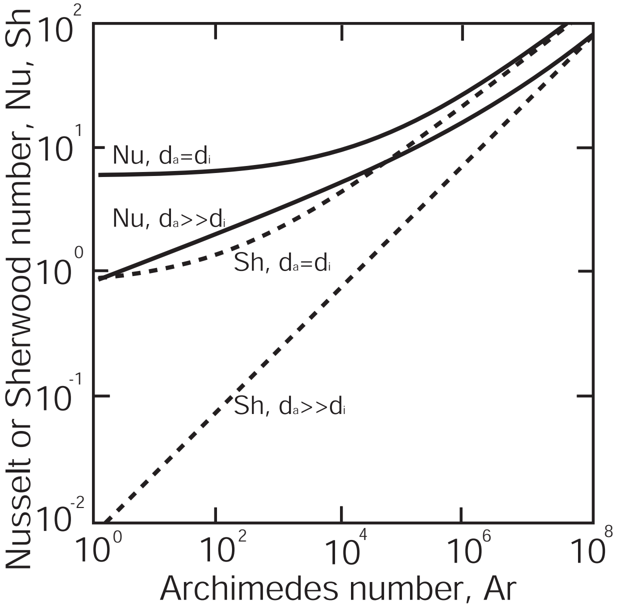
$$Nu_i = Nu_a d_i / d_a$$

$$\mathrm{Re}_{i,mf} = Re_{a,mf} d_i / d_a$$

$$\mathrm{Re}_{i,mf} = Ar / (1400 + 5.22 Ar^{0.5})$$

Baskakov-Palchonok’s approach: HEAT AND MASS TRANSFER INTERPOLATED BETWEEN $d_a=d_i$ and $d_a>>d_i$

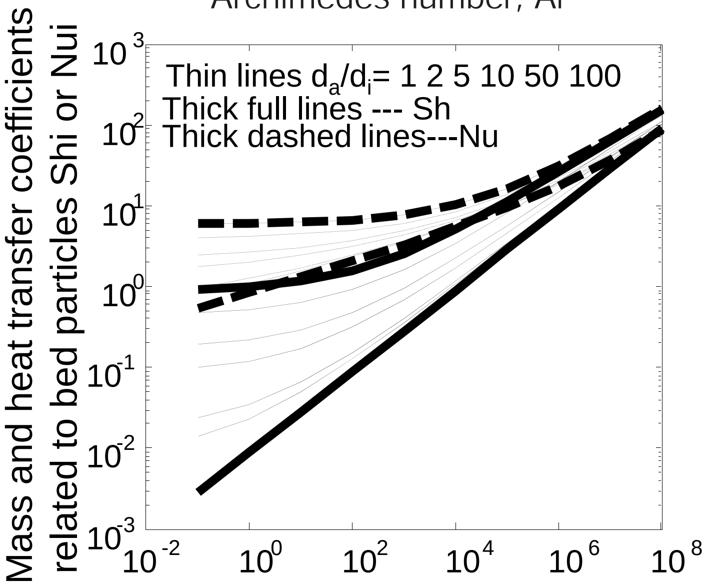
- Sh_1 or Nu_1 is the low limit $d_a=d_i$
- $Sh_{i,\infty}$ or $Nu_{i,\infty}$ is the large limit $d_a>>d_i$
- Sh_i or Nu_i are in between the limits



The interpolation formulae:

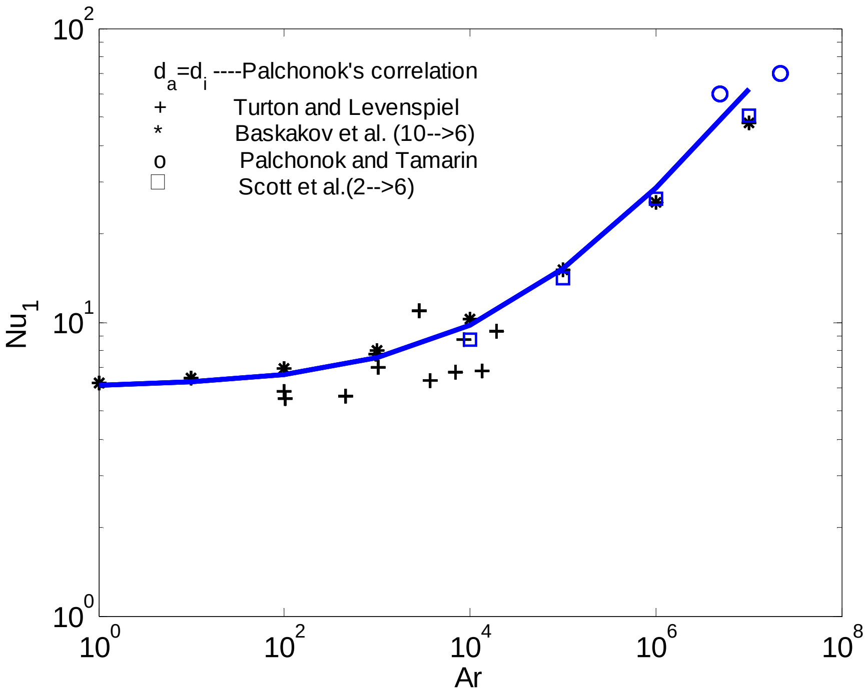
$$\frac{Nu_i - Nu_{i,\infty}}{Nu_1 - Nu_{i,\infty}} = (d_i / d_a)^n$$

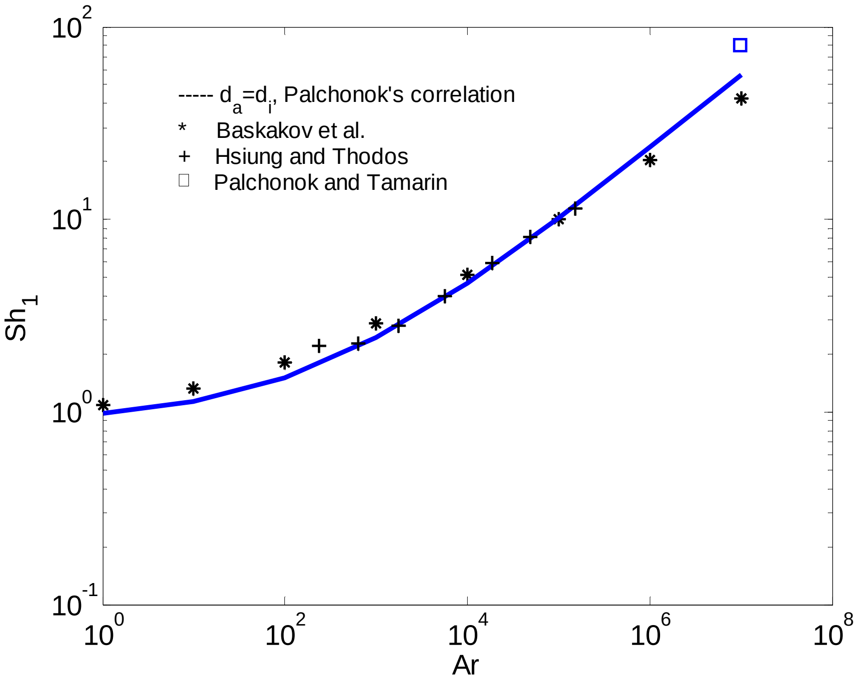
$$\frac{Sh_i - Sh_{i,\infty}}{Sh_1 - Sh_{i,\infty}} = (d_i / d_a)^m$$



Archimedes number Ar

THE d_i=d_a LIMIT





— fit to data in the limit d_a=d_i (Palchonok et al., 1992)

$$Nu_1 = 6 + 0.117 Ar_i^{0.39} Pr^{0.33}$$

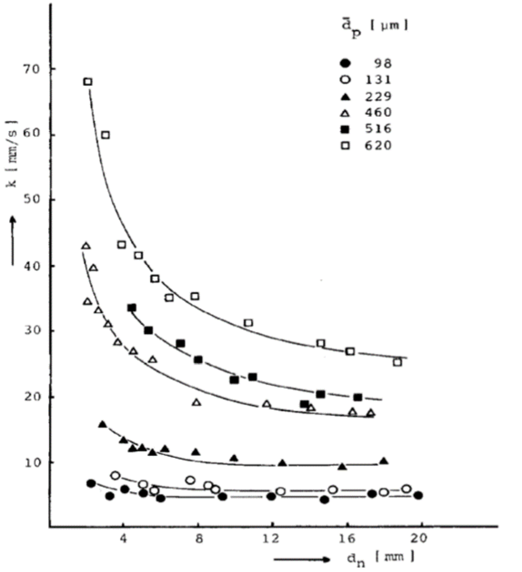
$$Sh_1 = 2\varepsilon_{mf} + 0.117 Ar_i^{0.39} Sc^{0.33}$$

THE LARGE ACTIVE PARTICLE LIMIT d_a>>d_i

Transfer to a large, fixed, and rounded object in a fluidized bed, Baskakov (1973),

$$Nu_{i,\infty} = 0.85 Ar^{0.19} + 0.006 Ar^{0.5} \Pr^{0.33}$$

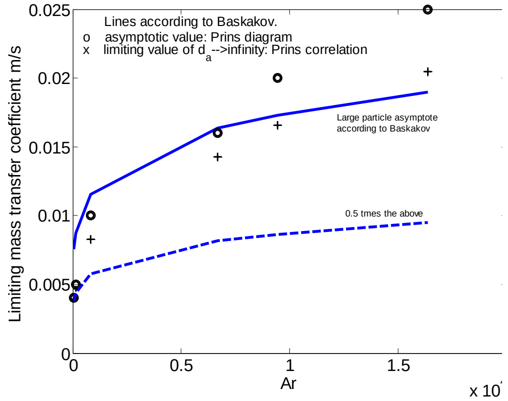
$$Sh_{i,\infty} = 0.009 Ar^{0.5} Sc^{0.33}$$

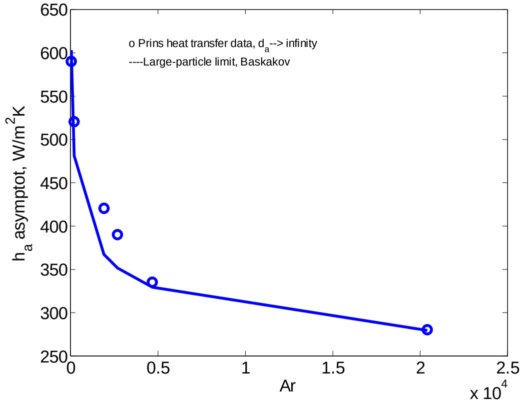


uence of the naphthalene sphere diameter on mass transfer coefficients in gas fluidized beds of glass beads; $U/U_{mf} - 2$.

(data from Prins 1987)

The mass (and heat) transfer coefficient goes to asymptotic values as $d_a \rightarrow \infty$





AVAILABLE HEAT TRANSFER CORRELATIONS

Scott et al. 2004

Tsukada and Horio, 1992

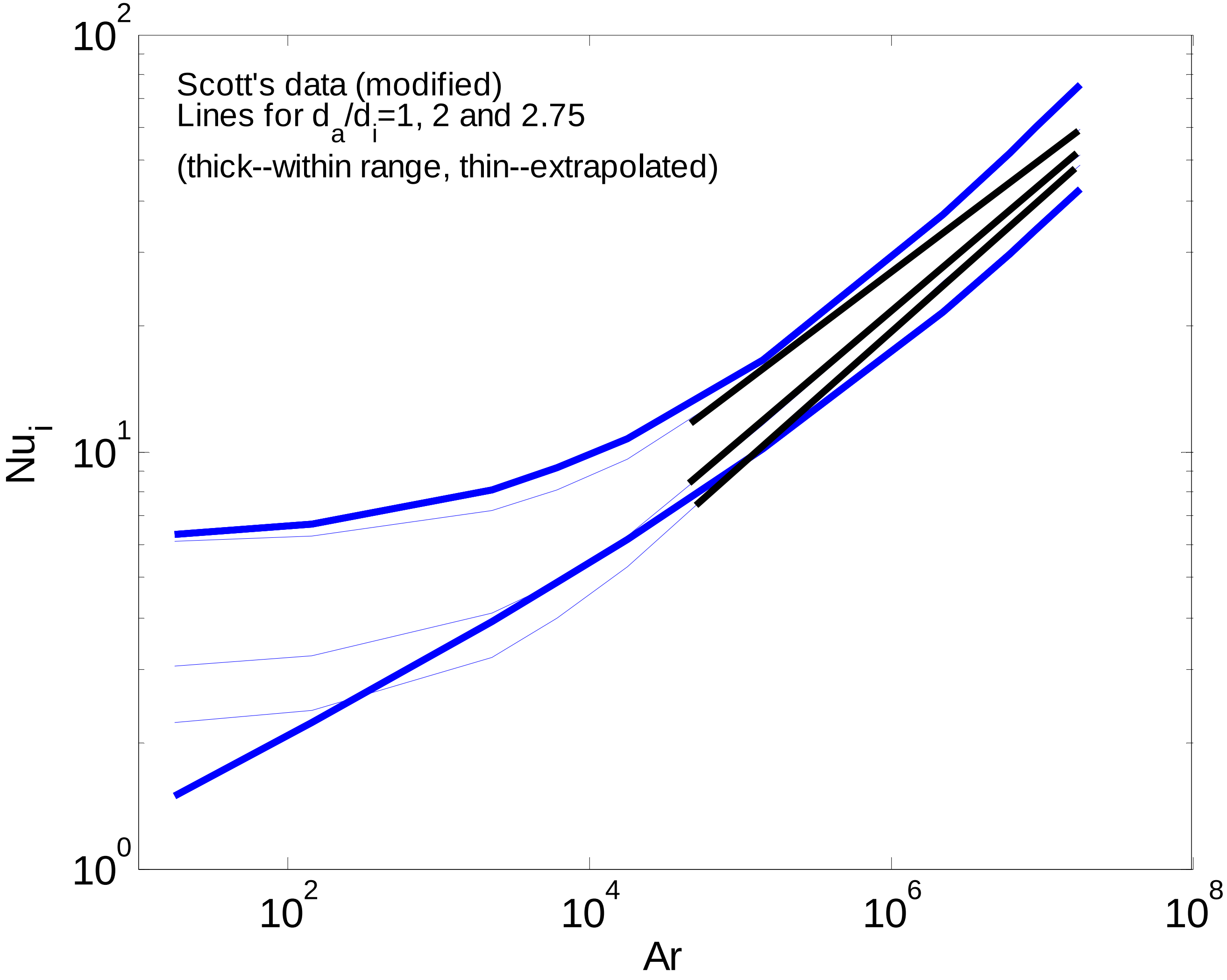
Prins, 1987

Babosa 1985

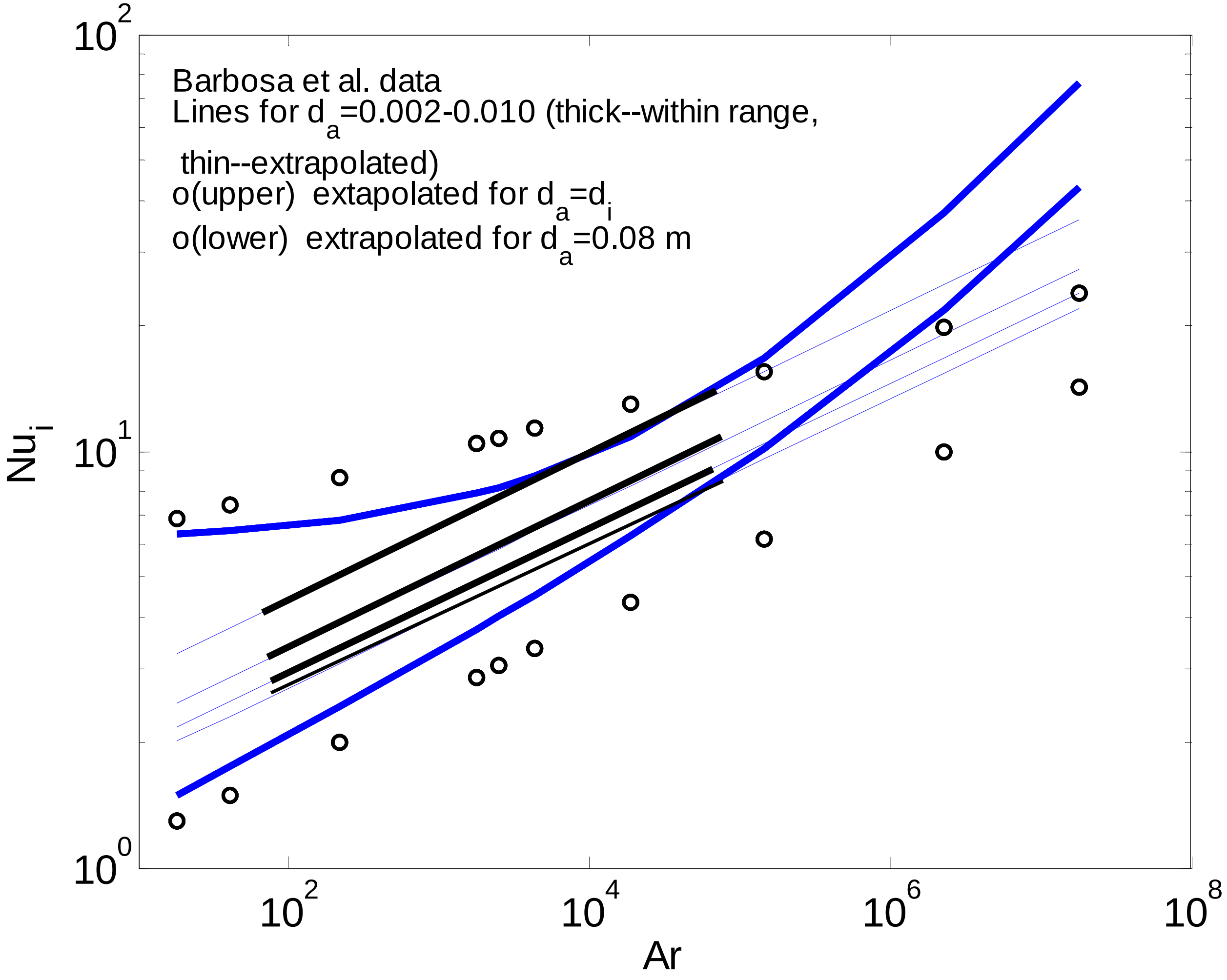
Shah, 1983

Palchonok and Tamarin, 1983

HT: Scott et al. 2004; $Nu_a = 2 + 1.0\,\mathrm{Re}_{mf,a}^{0.6}\left(\frac{d_a}{d_i}\right)^{0.26}$

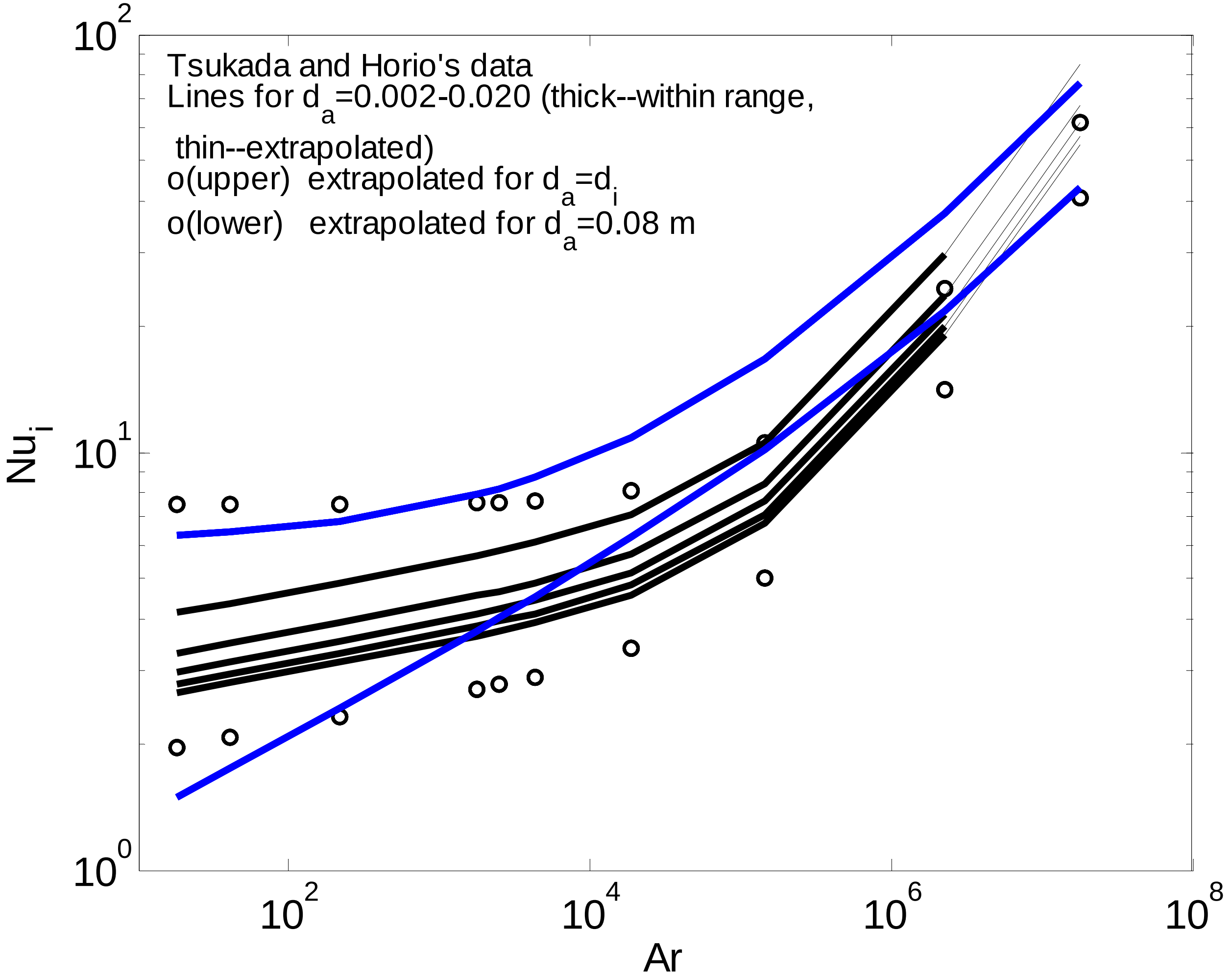


HT: Barbosa et al., 1995; $Nu_{i,\max} = 5.33 Ar^{0.09} (\frac{d_i}{d_a})^{0.25}$

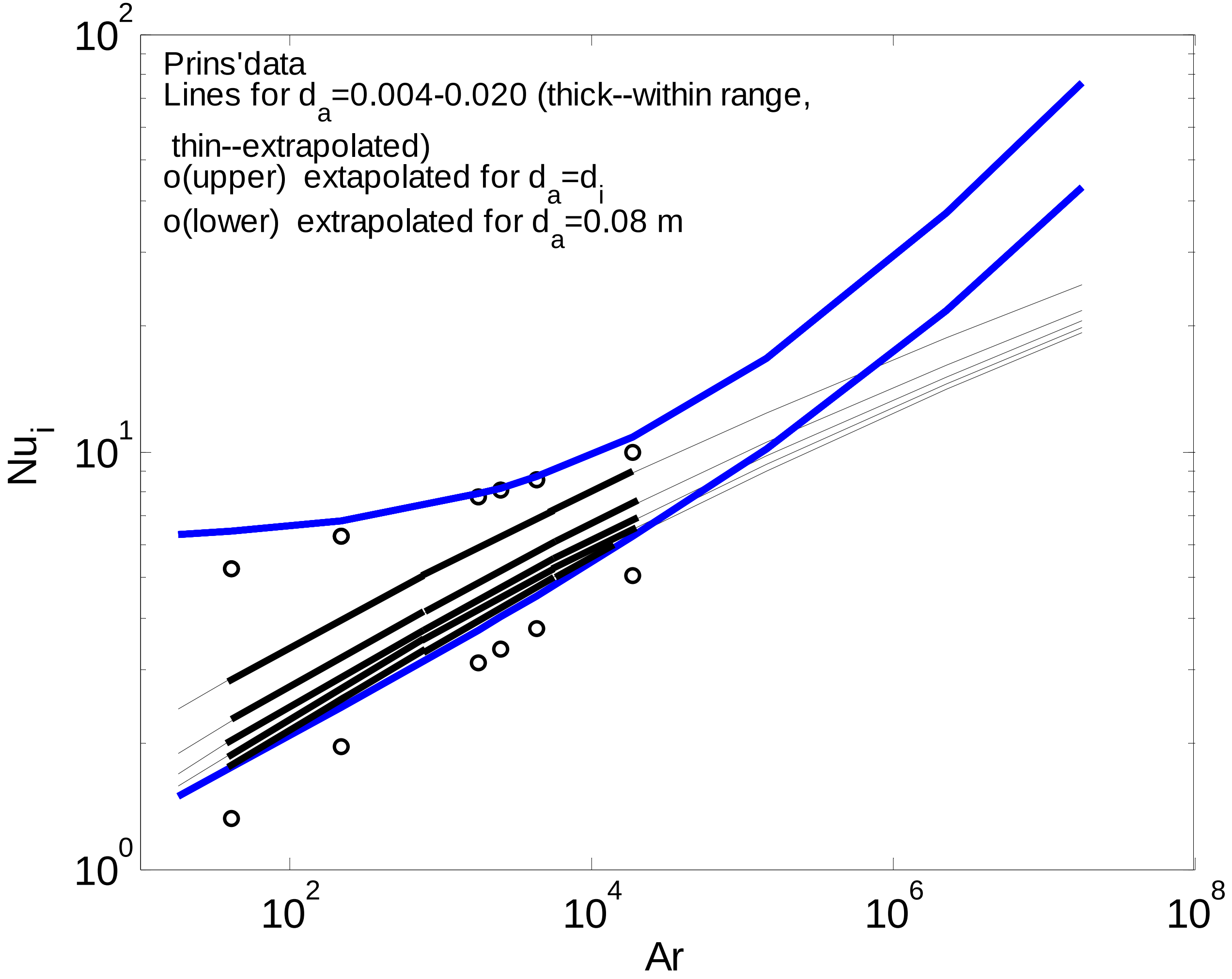


HT: Tsukada and Horio, 1992:

$$Nu_{a,\max} = (d_a / d_i)^{0.8}; \quad Nu_{i,\max} = (7.5 + 0.1 \Pr \mathrm{Re}_{mf})(d_i / d_a)^{0.2}$$

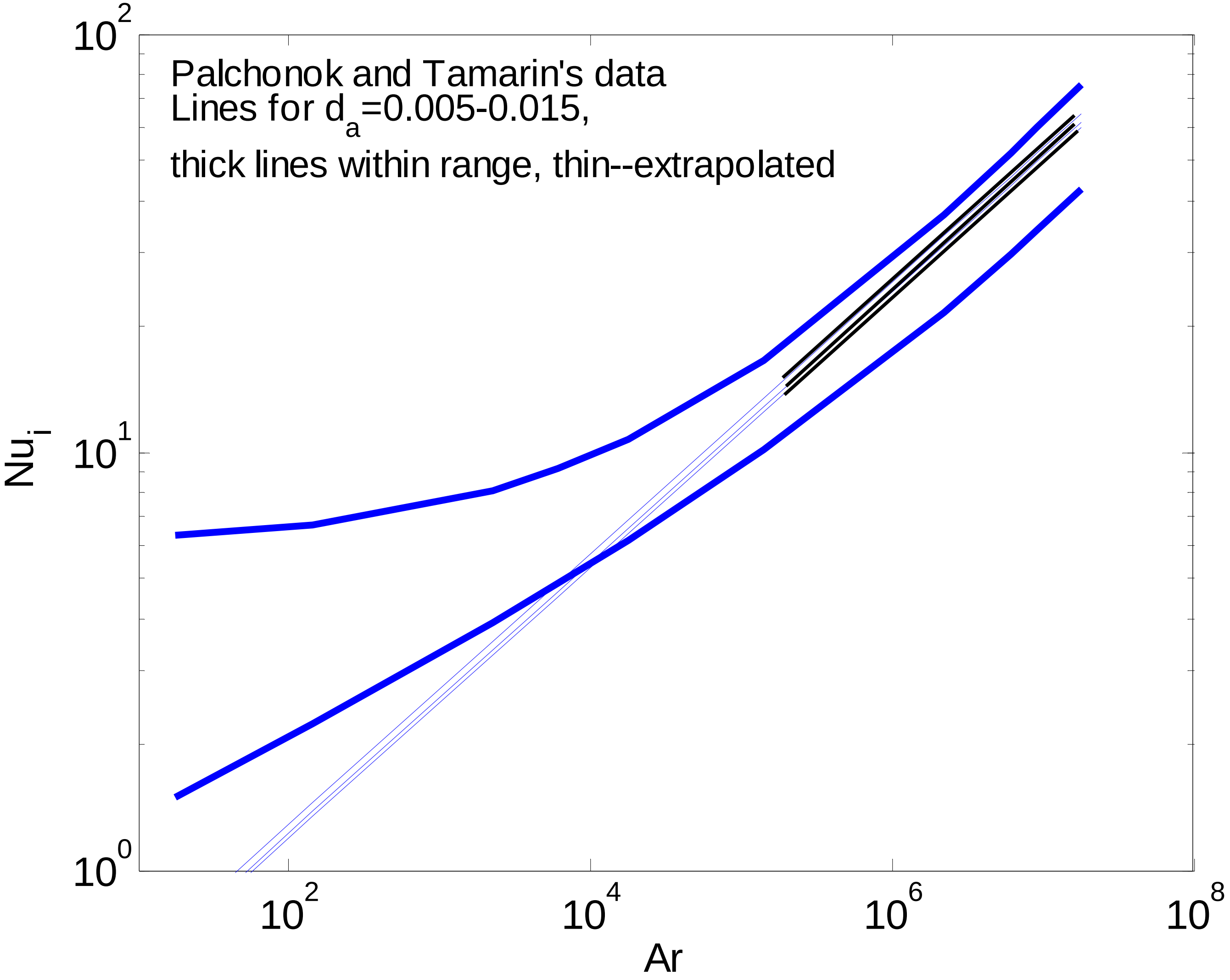


HT: Prins, 1987; $Nu_{i,\max} = 3.539\, Ar^{n} \left(\frac{d_i}{d_a}\right)^{0.257}$ *where* $n = 0.105\left(\frac{d_i}{d_a}\right)^{-0.062}$



HT:Palchonok and Tamarin, 1983;

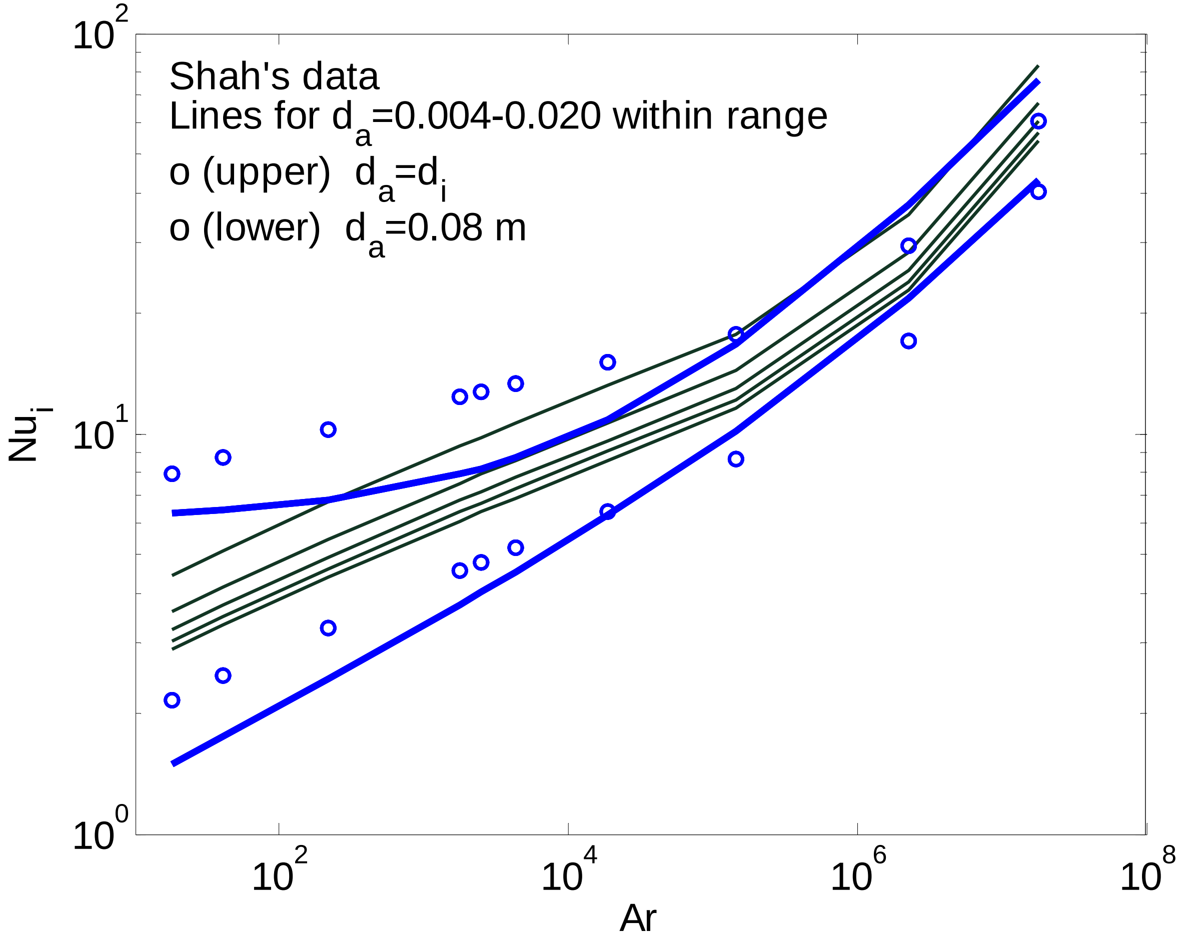
$$Nu_{i,\max} = 0.41 Ar^{-0.3} \left(\frac{d_i}{d_a}\right)^{0.2} \left(\frac{\rho_i}{\rho_a}\right)^{-0.07} \varphi^{0.66}$$



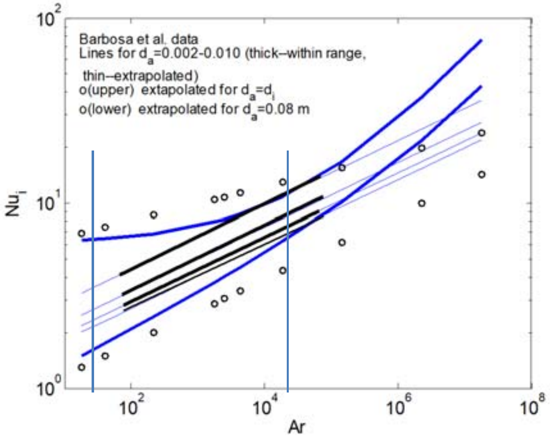
HT: Shah, 1983;

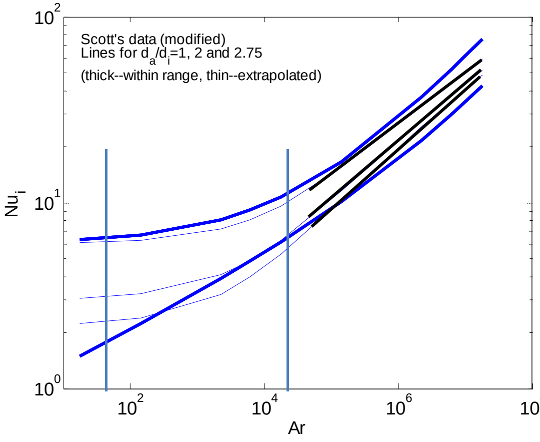
$$Nu_{i,\max} = 7.6\,\mathrm{Re}_{opt}^{0.158}\left(\frac{d_i}{d_a}\right)^{0.195}\left(\frac{c_{pa}}{c_{pi}}\right)^{0.18} \quad for \quad Ar < 40000$$

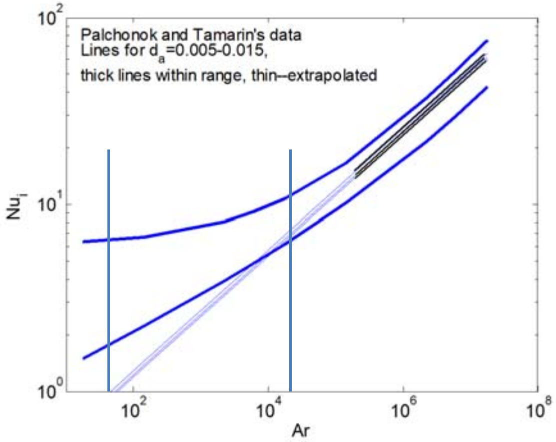
$$Nu_{i,\max} = 0.463\,\mathrm{Re}_{opt}^{0.695}\left(\frac{d_i}{d_a}\right)^{0.195} \quad for \quad Ar > 40000$$

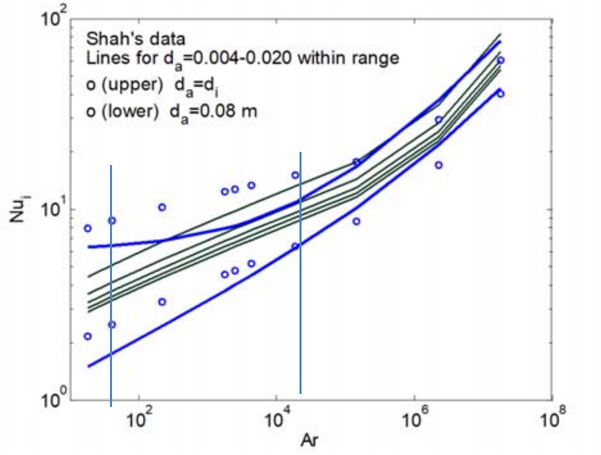


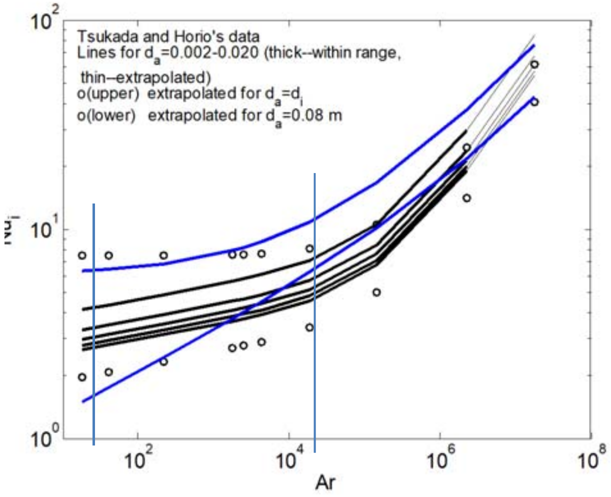
OVERVIEW OF THE PUBLISHED HEAT TRANSFER DATA

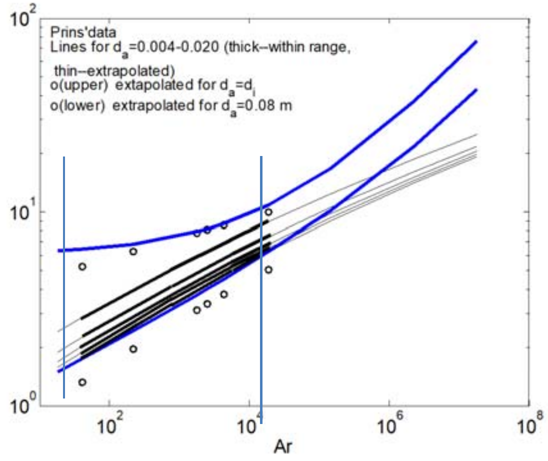






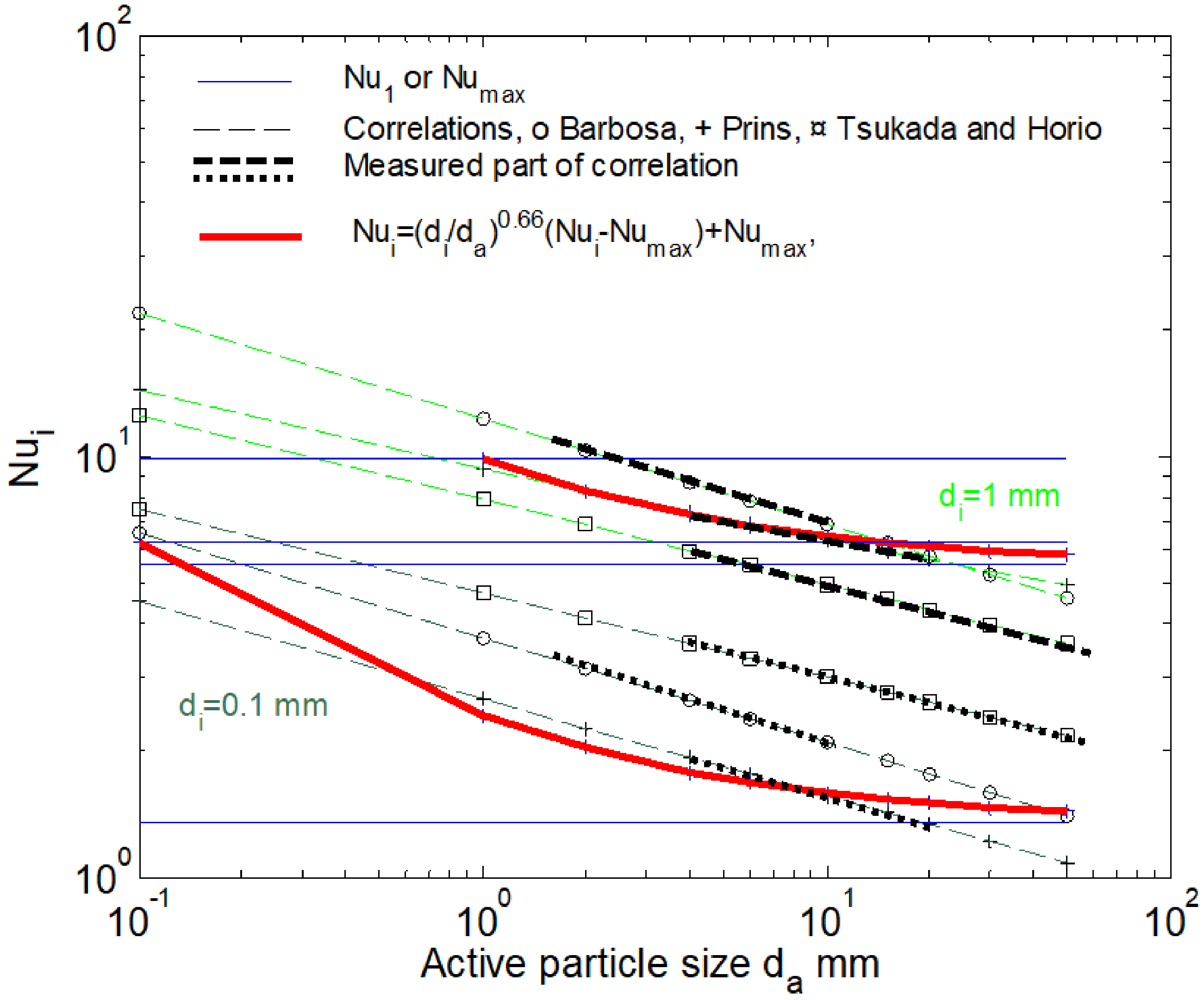






Fit of heat transfer data

$$Nu_i = Nu_{i,\infty} + (Nu_1 - Nu_{i,\infty})(d_i / d_a)^{0.66}$$



SELECTED MASS TRANSFER CORRELATIONS

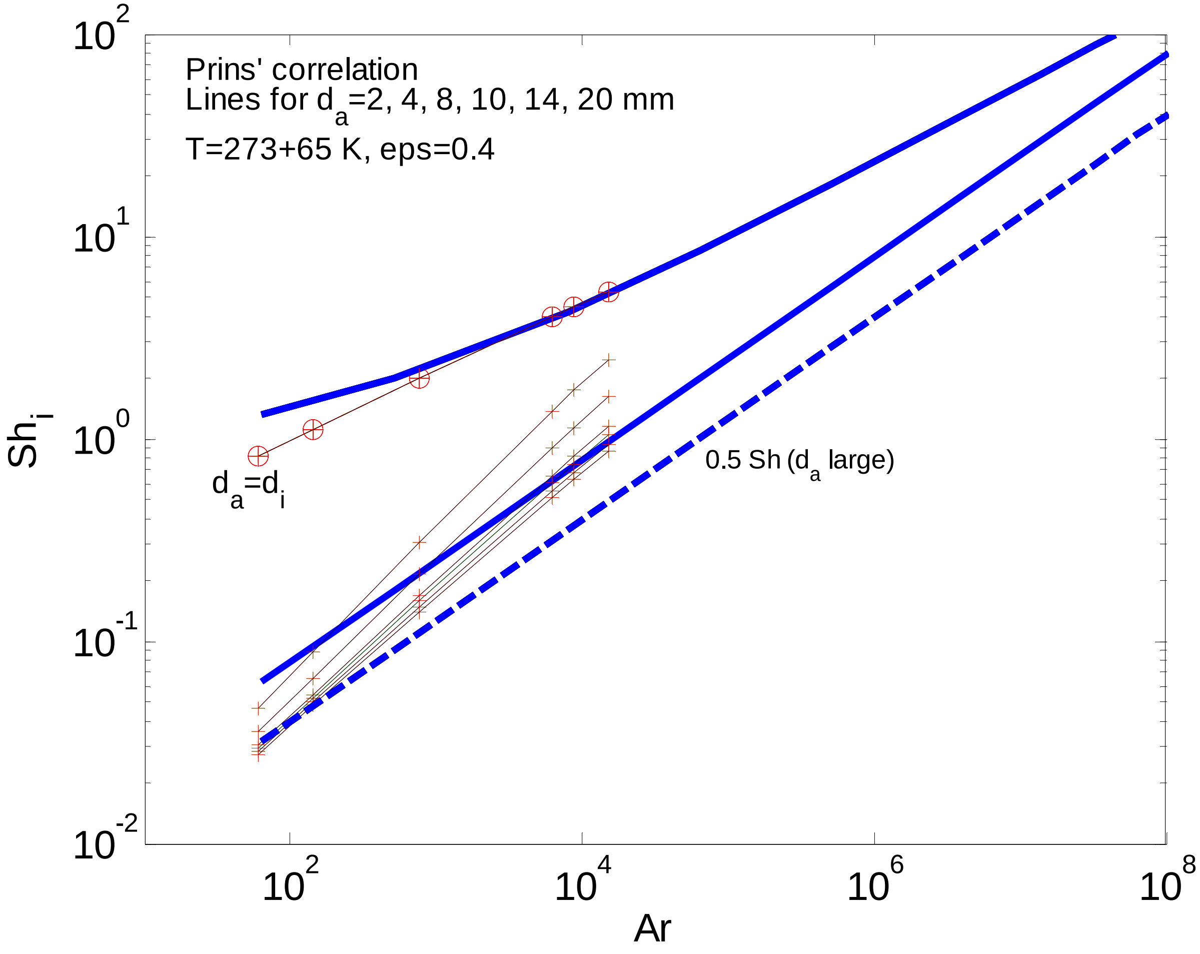
Scala 2007

Hayhurst and Parmar 2002

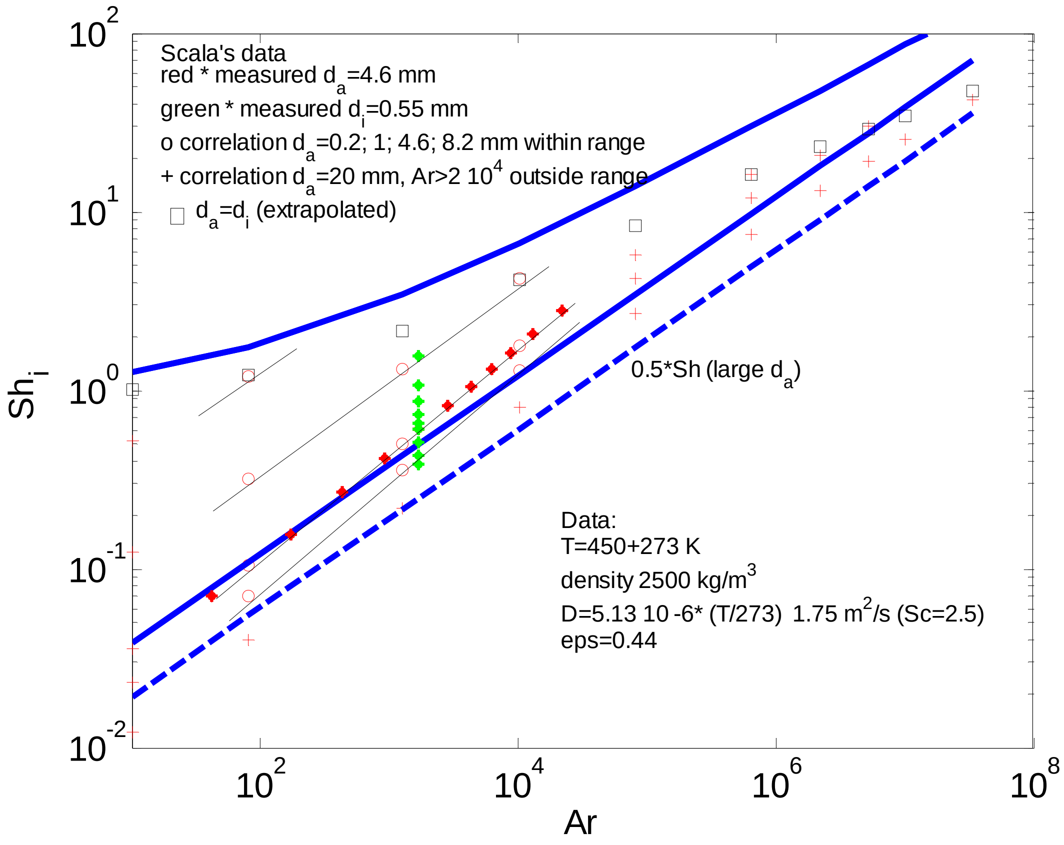
Prins 1987

MT: Prins 1987; $$Sh_i = \left[\frac{1-\varepsilon_{mf}}{\varepsilon_{mf}}\right]^m \left[\frac{\mathrm{Re}_{mf,i}}{\varepsilon_{mf}}\right]^{1-m} Sc^{0.33}(0.105+1.505(d_i/d_a)^{1.05})$$

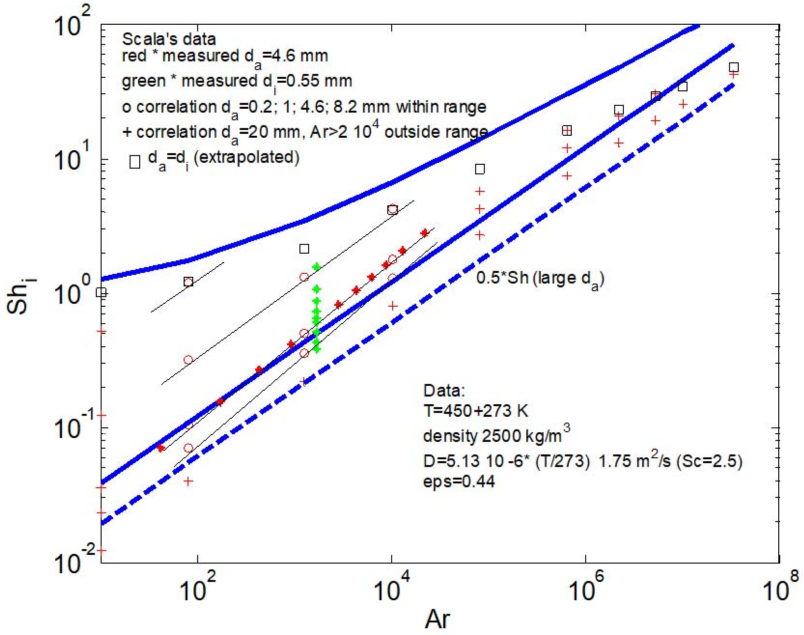
$$m = 0.35 + 0.29(d_i/d_a)^{0.5} \quad and \quad \mathrm{Re}_{mf,i} = u_{mf} d_i / \nu$$

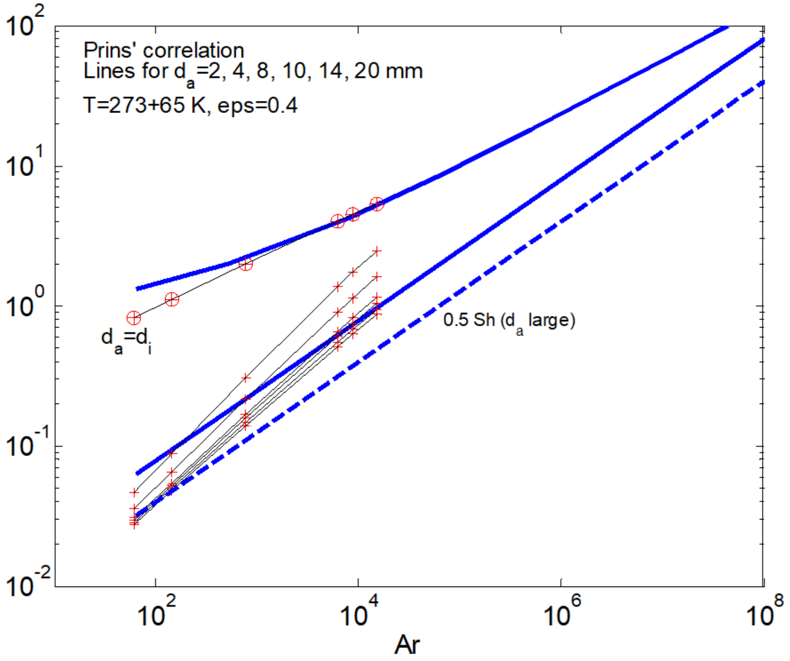


MT: Scala, 2007; $$Sh_a = 2.0\varepsilon_{mf} + 0.7\left(\frac{Re_{mf,a}}{\varepsilon_{mf}}\right)^{0.5} Sc^{0.3}$$



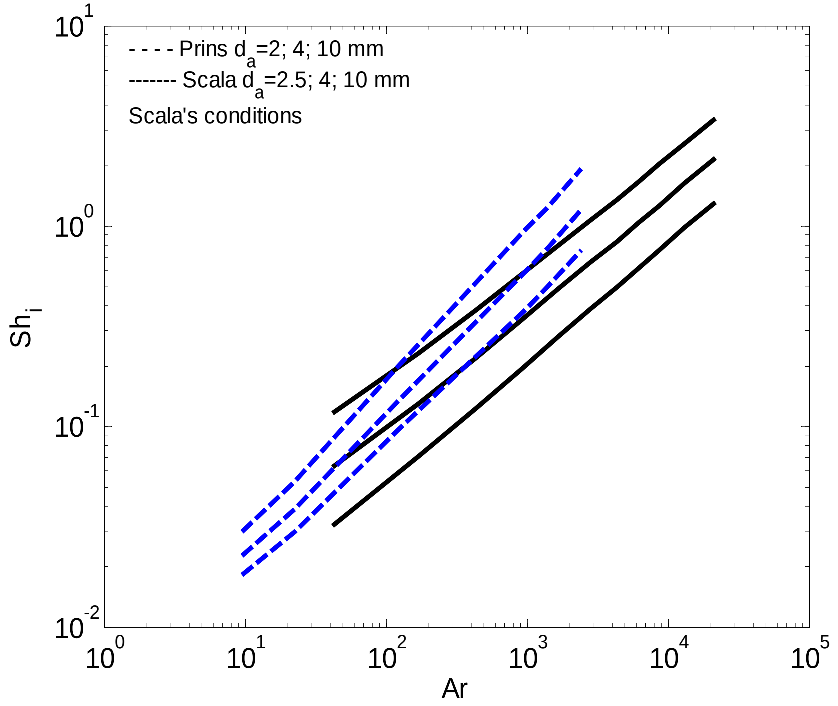
OVERVIEW OF THE MASS TRANSFER CORRELATIONS



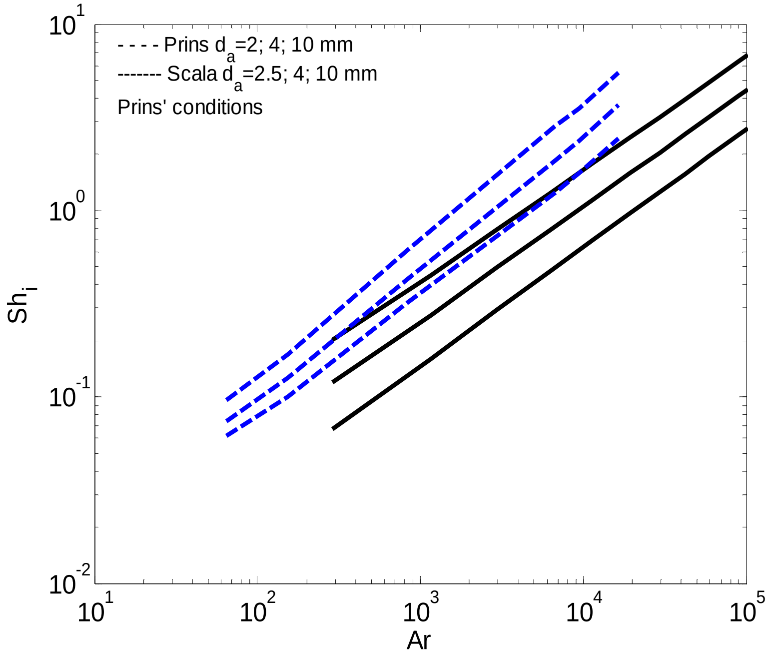


COMPARISON PRINS-SCALA

Scala’s conditions in both correlations



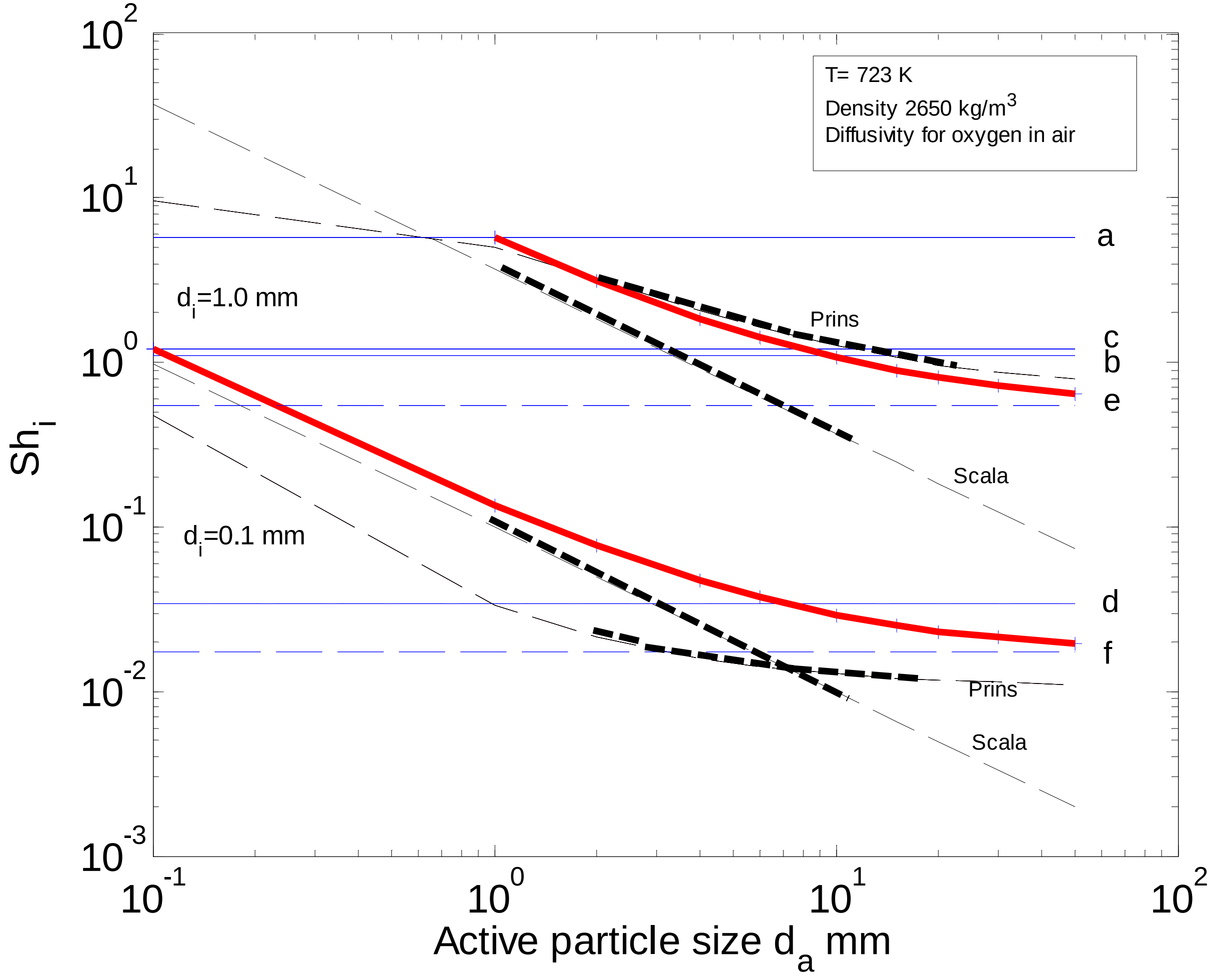
Prins’ conditions in both correlations



Quantity	**Scala**	**Prins**
Temperature, K	723	338
Bed particle density, kg/m^3	2500	2750
Voidage, -	0.44	0.40
Diffusivity, m^2/s	$9.4\cdot10^{-10}T^{1.75}$	$2.8\cdot10^{-10}T^{1.75}$
Sc	0.7	2.6

Fit of mass transfer data

$$Sh_i = Sh_{i,\infty} + (Sh_1 - Sh_{i,\infty})(d_i / d_a)^{1.0}$$



CONCLUSIONS

The agreement between available correlations on heat and mass transfer to active particles in fluidized beds is not extremely high.

However, the data in the measured ranges are at least within the limits of the Baskakov-Palchonok approach.

Therefore, an estimate of coefficients is obtained by

$$Nu_i = Nu_{i,\infty} + (Nu_1 - Nu_{i,\infty})(d_i / d_a)^{0.66}$$

$$Sh_i = Sh_{i,\infty} + (Sh_1 - Sh_{i,\infty})(d_i / d_a)^{1.0}$$

A seemingly more accurate estimation would be given by the correlation of choice, applied within its measured range.

It was shown that most correlations (exception Prins' for mass transfer) give erroneous values when extrapolated to large active particles.

Also, despite the dimensionless representation, the correlations depend on the properties of the media, e.g. the Schmidt number in the case of mass transfer.

Appendix: HEAT TRANSFER TO AN ACTIVE PARTICLE (a) IN A BED OF INERT PARTICLES (i): Model-free correlations

Some available correlations:

Tamarin et al. (1982)

$$Nu_i = 5Ar^{0.207}(\frac{d_a}{d_i})^{0.65}$$

Tamarin et al. (1985)

$$Nu_{i,\max} = 0.41Ar^{-0.3}(\frac{d_a}{d_i})^{-0.2}(\frac{\rho_a}{\rho_i})^{0.07}\varphi^{0.66}$$

Shah (1983)

$$Nu_{\max} = 7.6\,\mathrm{Re}_{opt}^{0.158}(\frac{c_{pa}}{c_{pi}})^{0.18}(\frac{d_a}{d_i})^{0.805} \quad for \quad \mathrm{Re}_{opt} < 170$$

$$Nu_{\max} = 0.463\,\mathrm{Re}_{opt}^{0.695}(\frac{d_a}{d_i})^{0.805} \quad for \quad \mathrm{Re}_{opt} > 170$$

Cobbinah et al. (1984)

$$Nu_{a,\max} = 3.254Ar^{0.104}(\frac{d_a}{d_i})^{0.464}$$

Prins (1985)

$$Nu_{i,\max} = 3.539Ar^{n}(\frac{d_a}{d_i})^{-0.257} \quad where \quad n = 0.105(\frac{d_a}{d_i})^{0.062}$$

Barbosa et al. (1993)

$$Nu_{\max} = 0.61Ar^{0.14}(\frac{d_a}{d_i})^{-0.15}(\frac{c_{p.i}\rho_i}{c_{p,g}\rho_g})^{0.17}$$

Scott et al. (2004), Collier et al. (2004)
(Cambridge)

$$Nu_a = 2 + 1.0\,\mathrm{Re}_{mf,a}^{0.6}(\frac{d_a}{d_i})^{0.26}$$

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