AIAA'88

AIAA-88-2618

Combined Natural and Forced Convection Heat Transfer from Isothermal Spheres

M.M. Yovanovich and
C.A. Vanoverbeke, Univ. of Waterloo
Waterloo, Ontario, Canada

**AIAA THERMOPHYSICS,
PLASMADYNAMICS AND LASERS
CONFERENCE**

JUNE 27-29, 1988/San Antonio, Texas

**For permission to copy or republish, contact the American Institute of Aeronautics and Astronautics
370 L'Enfant Promenade, S.W., Washington, D.C. 20024**

COMBINED NATURAL AND FORCED CONVECTION HEAT TRANSFER FROM ISOTHERMAL SPHERES

M.M. Yovanovich[1] and C.A. Vanoverbeke[2]
Microelectronics Heat Transfer Laboratory
Department of Mechanical Engineering
University of Waterloo
Waterloo, Ontario, N2L 3G1

Abstract

A simple correlation equation is proposed for mixed, crossflow, convection heat transfer from isothermal spheres. The equation is based on the linear superposition of the diffusive limit, the pure forced convection asymptote of Yuge and the natural convection asymptote developed by Raithby-Hollands and a term which accounts for natural convection effects on forced flow experiments. The proposed mixed convection heat transfer parameter $(Ra/Pe^2)^{1/4}$ accounts for the natural convection effects which are significant for Gr/Re^2 as low as 10^{-4}. The proposed correlation equation agrees well with air data in the range $2.4 \times 10^{-4} < Gr/Re^2 < 1.50$.

Nomenclature

a	correlation coefficient for mixed, cross flow, convection
b	correlation coefficient for mixed, cross flow, convection
C_1, C_2	pure forced and natural convection coefficients respectively
CR	mixed convection, cross flow, correction
D	sphere diameter $[m]$
Gr	Grashof number $[Gr = g\beta(T_0 - T_\infty)D^3/\nu^2]$
Gr/Re^2	natural/forced convection hydrodynamic parameter
g	gravity vector $[m/s^2]$
h	heat transfer coefficient $[W/m^2K]$
k	thermal conductivity $[W/mK]$
Nu	Nusselt number $[Nu = hD/k]$
N_G	Yuge natural convection parameter (0.392 $Gr^{0.25}$)
N_R	Yuge forced convection parameter (0.493 $Re^{0.5}$)
N_K	Yuge mixed convection parameter $(Nu - 2)$
Pe	Peclet number $[Pe = RePr]$
Pr	Prandtl number $[Pr = \nu/\alpha]$
Ra	Rayleigh number $[Ra = GrPr]$
$(Ra/Pe^2)^{1/4}$	mixed convection correction parameter
Re	Reynolds number $[Re = U_\infty D/\nu]$
T_0, T_∞	wall and free stream temperatures respectively $[K]$
U_∞	free stream velocity $[m/s]$

Greek Letters

α	thermal diffusivity of extensive fluid $[m^2/s]$
β	thermal expansion coefficient $[K^{-1}]$
Δ_0	Yuge mixed convection parameter $(N_K - N_R)$
μ	fluid viscosity $[Ns/m]$
ρ	fluid mass density $[kg/m^3]$
∞	free stream condition

Subscripts

EXP	experimental
FC	pure forced convection
MC	mixed convection
NC	pure natural convection
CGW	Clift, Grace and Weber correlation
RCL	Rowe, Claxton and Lewis correlation
$YUGE$	Yuge correlation

Superscript

0	mixed convection, cross flow, correlation before correction
∞	diffusive limit

Introduction

Steady, laminar, forced convection experimental heat transfer from isothermal spheres into air streams of large extent can be influenced by many factors such as i) free stream turbulence intensity, ii) radiation effects, iii) conduction along supports, iv) wind tunnel area blockage, and v) natural convection effects. The natural convection (NC) effects can be classified as a) aiding flow (AF) when the free stream velocity vector and the gravity vector are opposed (cooling problem); b) opposing flow (OF) when the free stream velocity and the gravity vectors are parallel (cooling problem); and c) cross flow (CF) when the velocity and gravity vectors are perpendicular, Figure 1.

---

[1] **Professor and Director. Associate Fellow AIAA**

[2] **Graduate Research Assistant**

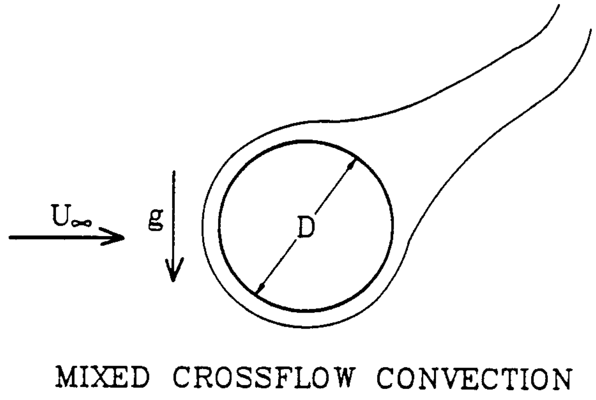

Fig. 1 Mixed crossflow convection schematic; velocity and gravity vectors are perpendicular

The major convective heat and mass transfer texts [1–5] state that the hydrodynamic, natural/forced, parameter Gr/Re^2 which appears in the dimensionless momentum equation can be used to determine whether free convection effects are significant in a forced convection experiment. For the case of flat plates, numerical solutions of the momentum and energy equations indicate that for Gr/Re^2 less than 0.02, natural convection effects are negligible, whereas for Gr/Re^2 greater than 100, forced convection effects are negligible on natural convection experiments.

The interested reader should consult Jaluria [3] and Burmeister [4] for a review of the many investigations on the subject of combined or mixed convection heat transfer from isothermal plates, cylinders and spheres. Since this paper is restricted to the problem of combined or mixed convection from isothermal spheres into extensive air streams, only those references which deal with this subject, and related topics such as pure forced and pure natural convection, will be considered [7–9].

Yuge [7] conducted pure natural convection, pure forced convection, and mixed convection experiments on heat transfer from isothermal spheres into extensive air streams at Reynolds numbers between 3.5 and 1.44×10^5, and Grashof numbers between 1 and 10^5. For mixed natural and forced convection, he studied three cases: 1) cross flow, 2) aiding flow and 3) opposing flow.

Based on his experimental results he proposed the following pure forced and natural convection correlations for area-mean Nusselt number:

Forced convection

$$Nu = 2 + 0.493Re^{0.5} \qquad 10 < Re < 1.8 \times 10^3 \qquad (1)$$

and

$$Nu = 2+0.300Re^{0.5664} \qquad 1.8\times 10^3 < Re < 1.5\times 10^5 \qquad (2)$$

Natural convection

$$Nu = 2 + 0.392Gr^{0.25} \qquad 1 < Gr < 10^6 \qquad (3)$$

The characteristic body length in the forced and natural convection correlations is the sphere diameter. All fluid properties are evaluated at the mean film temperature and $Pr = 0.715$.

Raithby and Hollands [9] proposed a pure natural convection correlation equation similar to Eq. (3) however the Grashof number coefficient was found to be 0.415.

In order to correlate the mixed convection data, Yuge introduced the following forced, natural and mixed convection parameters.

For forced convection,

$$N_R = 0.493\ Re^{0.5} \qquad (4)$$

For natural convection,

$$N_G = 0.392\ Gr^{0.25} \qquad (5)$$

For mixed convection,

$$N_K = Nu - 2 \qquad (6)$$

When $N_R = N_G$, then $\triangle_0 = (N_K - N_R)$.

The cross and parallel flow cases can be correlated by the following formulas:

1. $N_K = N_R + \triangle R$ for $N_R > N_G$
2. $N_K = N_G + \triangle G$ for $N_R < N_G$

where

$$\triangle R = \triangle_0 \exp[-n(N_R - N_G)] \qquad (7)$$

and

$$\triangle G = \triangle_0 \exp[-m(N_G - N_R)] \qquad (8)$$

The parameters m and n depend on the range of $N_G, \triangle_0$, and additional formulas are given for the evaluation of m and n.

Yuge's empirical method is clearly complicated and will not be used. The forced and natural convection correlation equations are in very good agreement with the results of other investigators such as Frössling [10] and Clift, Grace and Weber [12] who correlated the forced convection data of numerous investigators and recommended the two correlation equations:

$$Nu = 1 + 0.677Re^{0.47} \qquad 100 < Re \le 4000 \qquad (9)$$

and

$$Nu = 1 + 0.272Re^{0.58} \qquad 4 \times 10^3 < Re \le 1 \times 10^5 \qquad (10)$$

for $Pr = 0.7$. These correlations are based on air data for which the free stream turbulence intensity is less than 3%, negligible natural convection effects because $Gr/Re^2 < 0.1$, with rear support or free floating spheres, and wind tunnel blockage less than 10%. The Nusselt number predictions by the Yuge and the Clift, Grace and Weber correlation equations differ by less than 5% for $100 < Re < 1 \times 10^5$, therefore the Yuge correlation equations will be used in the subsequent sections. The air data of Rowe, Claxton and Lewis [8] in the Reynolds number range of 60 to 1750 are all significantly above the correlation curve of Yuge as shown in Figure 2.

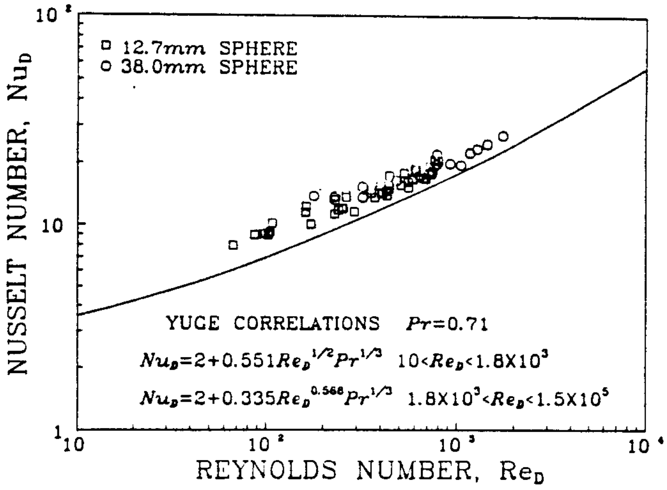

Fig. 2 Comparison of Rowe et al [8] air data against the Yuge [7] correlation equations

Rowe, Claxton and Lewis [8] assumed negligible natural convection effects and correlated their air data for two spheres (12.7 and 38.1 *mm* diameter) and obtained the correlation equation:

$$Nu = 2 + 0.69 Re^{0.5} Pr^{1/3} \tag{11}$$

which can be compared with correlation equations of Yuge. In the range $70 \leq Re \leq 1750$, the predictions of Eq. (11) are 17 to 24% above the predictions of Yuge [7], Eq. (1), and Clift, Grace and Weber [2], Eq. (9) are compared in Table 1, yet the equation predicts their forced convection data with an rms error of 9.5%.

Review of Experimental Parameters

The experimental data of Rowe, Claxton and Lewis [8] for two isothermal spheres (diameters of 12.7 and 38.1 *mm*) cooled by air streams were obtained for a range of the experimental parameters.

They reported 58 and 17 data points for the smaller and larger spheres respectively. The Reynolds number ranged from 228 to 1748 for the larger sphere, and from 67 to 801 for the smaller sphere. The bulk air temperature varied from a low of 19.8°C up to 25.7°C. The temperature difference between the sphere and the air was restricted to a narrow range of 2.43 – 5.01°C for the larger sphere; however, for the smaller sphere the temperature difference fell as low as 0.49°C, and was raised to a high value of 171.9°C. The measured Nusselt number was found to lie between the values 13.1 – 26.8 for the larger sphere, and between the values 7.9 – 20.6 for the smaller sphere.

The Grashof number Gr based on the sphere diameter ranged between 14.5 and 16,000 for the smaller sphere, and in the narrow range of 1.81×10^4 to 3.81×10^4 for the larger sphere. The often quoted mixed convection parameter Gr/Re^2 was found to range between 2.4×10^{-4} and 3.59 for all data.

Approximately 64% of the small sphere data had Gr/Re^2 values below 0.02 and only two values were equal to or greater than unity. The mixed convection parameter Gr/Re ranged from 0.010 to 0.720 for the larger sphere, and only 4 points had values below 0.020. Natural convection effects were observed to be significant at all points as seen in Figure 1 where the experimental results are compared with the pure forced convection correlation equations of Yuge [7], or Clift, Grace and Weber [2]. The difference between the measurements and the pure forced convection theory is approximately 22% over the full range of the experimental Reynolds number.

Mixed Convection Correlation

Because the Yuge [7] mixed convection, cross flow, correlation scheme is so complex and the others are not applicable, it was necessary to develop a mixed convection correlation equation. The proposed correlation equation will be based on the linear superposition of the diffusive limit, the pure forced convection correlation of Yuge [7] and pure natural convection correlation equations of Raithby and Hollands [9] giving,

$$Nu_{MC}^{\circ} = Nu_D^{\infty} + Nu_{FC} + Nu_{NC} \tag{12}$$

where $Nu_D^{\infty} = 2$ diffusive limit
$Nu_{FC} = C_1 Re_D^{1/2} Pr^{1/3}$ pure forced convection limit
$Nu_{NC} = C_2 Ra_D^{1/4}$ pure natural convection limit

The correlation coefficients for pure forced and natural convection are $C_1 = 0.551$ and $C_2 = 0.452$, respectively, obtained from the Yuge correlation equation and the Raithby-Hollands correlation.

Table 1 Comparison of forced convection correlation equations of Rowe, Claxton and Lewis [8], Yuge [7], and Clift, Grace and Weber [2].

Re	Nu_{RCL}	Nu_{YUGE}	Nu_{CGW}
70	7.15	6.12	5.99
100	8.16	6.93	6.90
300	12.7	10.5	10.9
500	15.8	13.0	13.6
700	18.3	15.0	15.7
900	20.5	16.8	17.6
1100	22.4	18.4	19.2
1300	24.2	19.8	20.7
1500	25.8	21.1	22.1
1700	27.4	22.3	23.3

It was observed that the above simple superposition of three independent heat transfer parameters gives values of Nu_{MC} which differ from the experimental values by approximately ±5% when the mixed convection parameter Gr/Re^2 is small (< 0.02). This occurred at 30% of the data points. For the remaining 53 data points positive or negative corrections were required to bring the experimental and theoretical values together.

Assuming that $Pe^{1/2}$ and $Ra^{1/4}$ which are forced and natural convection parameters, are more significant than Re^2 and Gr which fluid flow parameters in characterizing pure forced and natural convection heat transfer [6], a correction to the above simple mixed convection correlation equation was sought having the form

$$CR = a + b(\frac{Ra}{Pe^2})^{1/4} \tag{13}$$

For the air data, the parameter $(Ra/Pe^2)^{1/4}$ ranged between 0.136 and 1.50. It was observed that when this parameter is approximately unity, the correction is negative and approximately equal to the diffusive limit, that is -2. On the other hand at the lower value of approximately 0.30, the correction should be approximately zero; and approximately -3.4 at the upper value of 1.50.

The following simple expression:

$$CR = 0.86 - 2.86(\frac{Ra}{Re^2})^{1/4} \tag{14}$$

was found adequate to bring the remaining experimental points in line with the theory to within an rms difference of 6.8%.

The following mixed convection, cross flow, correlation equation is therefore proposed for the air data:

$$Nu_{MC} = Nu_D^\infty + Nu_{FC} + Nu_{NC} + CR \tag{15}$$

It will be compared with the air data of Rowe, Claxton and Lewis [8] which, to-date, have been treated as pure forced convection data. The pure forced convection correlation developed by them is inconsistent with respect to other pure forced convection correlations [2,7] as seen in Table 1.

Comparison of Predictions and Experimental Results

The proposed mixed convection, cross flow, correlation equation is compared with the experimental data and the pure forced convection correlation equation of Rowe, Claxton and Lewis [8] in Table 2. In the table, the Reynolds number, sphere diameters, temperature differences, and experimental Nusselt numbers Nu_{EXP} are reported with the predictions Nu_{RCL} of Rowe, Claxton and Lewis [8] and the proposed correlation predictions, Nu_{MC}. The data are presented according to the value of the Reynolds number to reveal interesting trends which cannot be easily seen as the data had been reported [8]. Several data are found to be inconsistent with respect to other data and the predictions of the two correlation equations.

The first inconsistent data point occurs at $Re = 108$ where it is seen that the Nu_{EXP} is approximately 10% greater than the Nu_{EXP} at $Re = 105$ and approximately 20% and 17% above the predictions by the pure forced convection correlation of Rowe et al [8] and the proposed mixed convection correlation equation. At $Re = 123$ the experimental and pure forced convection values are approximately 11% below the mixed convection prediction. At $Re = 263$, the Nu_{EXP} is approximately 16% and 19% above the forced and mixed convection predictions respectively, which differ by approximately 3%.

The data at $Re = 291, 321$ and 322 are also inconsistent. For $Re = 291$ the Nu_{EXP} is significantly below the $Re = 264$ data, and 8% and 17% below the forced and mixed convection predictions which differ by approximately 9%.

The Nu_{EXP} at $Re = 321$ and 322 should be identical, but one finds that the $Re = 321$ data point is in excellent agreement with the Nu_{MC} values at $Re = 321$ and 322.

The Nu_{EXP} value at $Re = 432$ is quite inconsistent with respect to the data points at lower and higher Reynolds numbers, as well as with the two predictions which differ by approximately 8%. It should be noted that the temperature difference is very large in this case.

The Nu_{EXP} values at $Re = 443$ should be identical, but one notes that the second value is approximately 15% greater than the first value which is in very good agreement with both predictions.

The Nu_{EXP} values at $Re = 528, 529, 602, 610$ and 722 lie approximately 5 to 10% above the Nu_{RCL} values which in turn lie approximately 7% above the Nu_{MC} values. However, when the Nu_{EXP} values are compared with data at lower and higher Reynolds numbers, one observes that they are approximately $9 - 12\%$ too high.

At $Re = 765$ and 769, Nu_{EXP} is found to be approximately 6% above neighboring experimental data and also above the predictions which differ by approximately 8%. The last inconsistent data point is found at $Re = 1049$ where Nu_{EXP} is slightly below the $Re = 922$ value and

Table 2: Comparison of experimental Nusselt numbers with predictions of Rowe, Claxton and Lewis (1965) and proposed mixed convection correlation equation.

Re_D	D (mm)	ΔT $(^\circ C)$	$(\frac{Ra}{Pe^2})^{1/4}$	Nu_{EXP}	Nu_{RCL}	Nu_{MC}	Re_D	D (mm)	ΔT $(^\circ C)$	$(\frac{Ra}{Pe^2})^{1/4}$	Nu_{EXP}	Nu_{RCL}	Nu_{MC}
67	12.7	171.90	1.50	7.9	7.0	7.2	443	12.7	1.22	0.22	17.2	15.0	14.4
87	12.7	75.22	1.25	8.9	7.7	8.3	483	38.1	3.99	0.65	16.3	15.6	17.3
97	12.7	33.33	1.03	9.0	8.1	8.6	511	12.7	45.03	0.47	15.5	15.9	16.7
99	12.7	33.65	1.03	9.0	8.1	8.7	528	12.7	1.12	0.20	17.8	16.2	15.4
103	12.7	15.68	0.85	9.0	8.3	8.7	529	12.7	0.60	0.17	16.9	16.2	15.2
103	12.7	11.76	0.80	8.9	8.3	8.7	529	12.7	1.11	0.20	17.7	16.2	15.4
105	12.7	8.66	0.74	9.2	8.3	8.7	556	12.7	18.72	0.38	16.1	16.5	16.8
108	12.7	3.35	0.57	10.1	8.4	8.6	557	12.7	103.70	0.51	15.1	16.5	17.6
162	12.7	1.75	0.40	11.4	9.9	9.9	587	12.7	6.39	0.29	16.5	16.9	16.7
163	12.7	0.84	0.33	12.2	9.9	9.8	589	12.7	8.39	0.31	16.5	17.0	16.8
173	12.7	144.98	0.93	10.0	10.1	11.3	589	12.7	4.92	0.27	16.7	17.0	16.6
179	38.1	4.83	1.13	13.7	10.3	12.0	602	12.7	1.83	0.21	18.4	17.1	16.3
228	38.1	4.80	0.99	13.5	11.3	13.2	610	12.7	0.53	0.16	18.7	17.2	16.1
230	38.1	5.01	1.00	13.1	11.4	13.3	610	12.7	1.19	0.19	18.1	17.2	16.3
230	12.7	60.76	0.74	11.2	11.3	12.5	638	38.1	3.85	0.57	17.2	17.6	19.2
232	38.1	4.81	0.99	13.7	11.4	13.3	667	12.7	41.90	0.41	16.8	17.9	18.4
241	12.7	25.57	0.62	11.7	11.6	12.4	688	12.7	0.91	0.17	16.8	18.2	17.0
251	12.7	11.83	0.51	11.9	11.8	12.3	689	12.7	0.50	0.14	16.6	18.2	16.8
254	12.7	8.76	0.48	12.0	11.8	12.3	715	12.7	17.30	0.33	17.6	18.5	18.5
255	12.7	6.79	0.45	12.0	11.9	12.2	715	12.7	17.35	0.33	17.5	18.5	18.5
263	12.7	0.71	0.25	13.9	12.0	11.7	722	12.7	1.03	0.17	19.1	18.6	17.3
264	12.7	1.55	0.31	13.5	12.0	11.9	734	12.7	7.62	0.27	17.8	18.7	18.2
291	12.7	125.40	0.71	11.5	12.5	13.8	734	12.7	7.77	0.27	17.5	18.7	18.3
321	38.1	4.29	0.81	15.2	13.1	14.9	742	12.7	5.93	0.25	18.0	18.8	18.2
322	38.1	4.88	0.84	13.5	13.1	15.1	746	12.7	4.55	0.24	18.1	18.9	18.1
356	12.7	0.71	0.22	14.2	13.6	13.1	759	38.1	3.44	0.50	19.0	19.0	20.3
357	12.7	1.36	0.25	14.7	13.7	13.3	765	12.7	1.02	0.16	20.6	19.1	17.7
373	12.7	51.38	0.57	13.5	13.9	14.9	769	12.7	0.49	0.14	20.3	19.1	17.6
398	12.7	1.29	0.24	15.4	14.3	13.8	783	38.1	3.36	0.49	19.5	19.3	20.5
406	12.7	21.44	0.46	14.1	14.4	15.0	784	38.1	2.94	0.48	21.8	19.3	20.4
410	12.7	21.25	0.46	14.3	14.5	15.1	801	12.7	1.64	0.18	20.3	19.5	18.2
427	12.7	9.73	0.38	14.5	14.7	14.9	922	38.1	3.32	0.45	19.7	20.7	21.8
430	12.7	7.21	0.35	14.6	14.8	14.9	1049	38.1	3.35	0.42	19.4	22.0	22.9
430	12.7	7.21	0.35	14.6	14.8	14.9	1172	38.1	2.97	0.39	22.2	23.1	23.7
432	12.7	5.59	0.33	14.6	14.8	14.8	1278	38.1	2.82	0.37	23.1	24.1	24.4
432	12.7	111.30	0.58	13.8	14.8	16.0	1446	38.1	2.72	0.35	24.4	25.5	25.6
439	12.7	2.18	0.26	15.5	14.9	14.5	1748	38.1	2.43	0.30	26.8	27.8	27.4
443	12.7	0.66	0.19	14.9	15.0	14.2							

approximately 13% below the correlation values which are in excellent agreement.

Excluding the above 23 experimental points, one finds that Nu_{EXP}, Nu_{RCL} and Nu_{MC} are in good to very good agreement over the full range of Reynolds number. The largest discrepancies between Nu_{EXP} and Nu_{MC} appear to occur when the temperature differences are large, eg., at $Re = 173, 230, 241, 291, 432, 511, 557$, and 667. When the temperature differences are large, the reported Nusselt numbers are observed to be much lower than neighboring experimental values, and lower than Nu_{MC} by as much as 13%. At these points Nu_{EXP} and Nu_{RCL} are either in very good agreement or differ significantly.

The data for the lowest Reynolds numbers, $67 \leq Re \leq 103$, which also correspond to the largest temperature differences, $11 < \Delta T < 172$, are in very good agreement with Nu_{MC}, and good agreement with Nu_{RCL}.

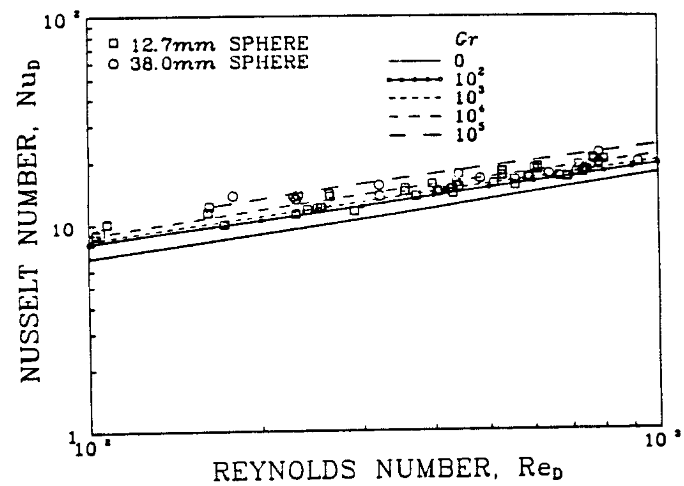

Fig. 3 Comparison of proposed mixed, crossflow, correlation equation and the mixed convection air data of Rowe et al [8].

The proposed mixed, crossflow, correlation equation for isothermal spheres, Eq. (15) with Eq. (14) is compared with the air data in Figure 3. The natural convection effect on the forced convection are clearly seen over the full range of the data. The agreement between the proposed correlation equation and the air data of Rowe et al [8] is seen to be very good.

Summary and Conclusions

The proposed mixed convection, cross flow, correlation equation, Eq. (15), is based on the linear superposition of the pure diffusive, pure forced and pure natural convection asymptotes as well as a mixed convection, cross flow, correction term which accounts for heat transfer enhancement when natural convection effects are much smaller than the forced convection, and heat transfer degradation when natural convection effects are comparable.

The correction term is based on the parameter $(Ra/Re^2)^{1/4}$ rather than the often-quoted mixed convection parameter Gr/Re^2. The correction (positive or negative) is required for all data points in the range $2.4 \times 10^{-4} < Gr/Re^2 < 3.6$ or $0.13 < (Gr/Re^2)^{1/4} < 1.5$ for $Pr = 0.71$. At the lower end the correction is slightly positive (0.5) indicating a small enhancement and at the higher end the correction is quite negative (−3.4) indicating a significant interference between the forced and natural convection flow fields.

The rms percent difference between the pure forced convection correlation of Rowe et al, Eq. (11), and their air data is approximately 9.5% and the rms difference between the proposed mixed convection, cross flow, correlation, Eq. (15) and the same data is approximately 9.6%. The rms percent difference between the pure forced and the proposed mixed convection correlation equations is approximately 6.8% over the experimental range of the parameter Gr/Re^2. The largest difference (> 7%) between the two correlation equations occurs at 16 data points, and a difference of 10 – 17% occurs at 10 of the 16 data points. These points correspond to large values of Gr/Re^2 where there is significant natural convection effects (interference), and the pure forced convection correlation is expected to be less accurate.

The proposed mixed convection, cross flow, correlation equation is as accurate as the pure forced convection correlation equation when all data are considered. However, when the data corresponding to large values of Gr/Re^2 are considered, the proposed correlation equation is superior.

The statement that "forced flow correlations are accurate to about 10% for $Gr/Re^2 < 0.2$" appears in the text of Clift et al [2] is found to be inaccurate for the Rowe at al [8] air data. Natural convection effects in cross flow are observed to be significant for Gr/Re^2 as low as 10^{-4}. Additional studies of mixed convection heat transfer are required to elucidate the physical phenomena and provide data for evaluation or refinement of the proposed correlation equations.

Acknowledgements

The authors acknowledge the continued support of the Natural Sciences and Engineering Research Council of Canada under operating grant A7445 to Dr. Yovanovich.

References

1. Skelland, A.H.P., *Diffusional Mass Transfer*, John Wiley & Sons, New York, (1974).
2. Clift, R., Grace, J.R. and Weber, M.E., *Bubbles, Drops and Particles*, Academic Press, New York, (1978).
3. Jaluria, Y., *Natural Convection Heat and Mass Transfer*, Pergamon Press, New York, (1980).
4. Burmeister, L.C., *Convective Heat Transfer*, John Wiley & Sons, New York, (1983).
5. Arpaci, V.S., and Larsen, P.S., *Convection Heat Transfer*, Prentice Hall, Inc., Englewood Cliffs, NJ, (1984).
6. Bejan, A., *Convection Heat Transfer*, John Wiley & Sons, New York, (1984).
7. Yuge, T., "Experiments on Heat Transfer from Spheres including Combined Natural and Forced Convection," *Trans. ASME* **82**, ser. C, 214–20 (1960).
8. Rowe, P.N., Claxton, K.T., and Lewis, J.B., "Heat and Mass Transfer from a Single Sphere in an Extensive Fluid," *Trans. Inst. Chem. Engrs.*, **43**, T14–T31 (1965).

9. Raithby, G.D., and Hollands, K.G.T., "A General Method of Obtaining Approximate Solutions to Laminar and Turbulent Free Convection Problems," in: *Advances in Heat Transfer*, Vol. 11, eds. T.F. Irvine and J.P. Hartnett, Academic Press, 266–315 (1975).

10. Frössling, N., "The Evaporation of Falling Drops," *Gerlands Beitr. Geophys.*, **52**, 170 (1938).

11. Yovanovich, M.M., "Natural Convection from Isothermal Spheroids in the Conductive to Laminar Flow Regimes," AIAA-87-1587, AIAA 22nd Thermophysics Conference, June 8–10, 1987, Honolulu, Hawaii.

12. Yovanovich, M.M., "General Expression for Forced Convection Heat and Mass Transfer from Isopotential Spheroids," AIAA-83-0743, AIAA 26th Aerospace Sciences Meeting, January 11–14, 1988, Reno, Nevada.