"POWER LAW" PROFILES IN THERMALLY STRATIFIED SHEAR FLOWS

by

H. Chuang and J. E. Cermak

fig 6 p21
fig 7 p22

Prepared for

U. S. Army Research Grant

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FLUID MECHANICS PROGRAM
ENGINEERING RESEARCH CENTER
COLLEGE OF ENGINEERING
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

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Fluid Dynamics and Diffusion Laboratory
College of Engineering
Colorado State University
Fort Collins, Colorado

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ABSTRACT

A "power law" model is used to describe the wind and temperature profiles in thermally stratified shear flows for bulk Richardson numbers from - 0.8 to 0.2. It is shown that the power of wind and temperature profiles were not independent of the thermal stability and that similarity between wind and temperature profiles is good. Functional dependence of the power upon the thermal stability is shown for data of Prairie Grass and laboratory measurements.

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INTRODUCTION

The authors (1) compared the KEYPS model (2) with the log-linear model (3) and showed that the latter described the wind and temperature profiles in thermally stratified shear flows better than the former did. The historically old "power law" has recently been revived by Pandolfo (4). His profile has a minus one-sixth power instead of the minus one-third power profile of free convection tested by Taylor (5). He claimed that the minus one-sixth "power law" described the observed wind profiles quite accurately and that it was more accurate to describe the wind profile than Taylor's free convection model (5) or Swinbank's exponential model (6). The Swinbank exponential wind profile predicts the wind speed being proportional to ln [exp (Z/L) - 1] such that, when Z/L is much smaller than unity, it behaves like a logarithmic profile, but when Z/L is greater than unity, it is directly proportional to Z/L. Pandolfo also compared his profile with KEYPS profile and concluded that these two models were comparable to each other pertaining to their accuracy of a wind profile description.

It is interesting to show that the "power law" model can indeed describe the wind profiles accurately. However, it is important to point out that the power should not be a constant in all ranges of thermal stability, but it should rather be dependent on the thermal stability and should approach the minus one-third profile as the flow field approaches a free convection. Therefore, the power profile is examined in this paper. Similarity between wind and temperature profiles is also studied.

BASIC EQUATIONS

If the dimensionless wind shear, S, and lapse rate R, defined (1) as

$$S = \frac{kZ}{u_*} \frac{\partial U}{\partial Z} ,$$

and

$$R = \frac{\alpha Z}{T_*} \frac{\partial T}{\partial Z} ,$$

are assumed to be proportional to ζ^n, then the mean wind velocity, U, and temperature, T, will take the following forms:

$$U(Z) - U_o(Z_o) = \frac{\beta' u_*}{k\ n} (\zeta^n - \zeta_o^n) , \qquad (1)$$

and

$$T(Z) - T_o(Z_o) = \frac{\gamma' T_*}{\alpha n} (\zeta^n - \zeta_o^n) , \qquad (2)$$

where k is von Karman's constant; u_*, the friction velocity; Z, height; T_*, the friction temperature; α the ratio of eddy conductivity, K_h, to eddy viscosity, K_m; β' and γ', constant proportionality; $\zeta = Z/L'$; $\zeta_o = Z_o/L'$; and L', a length scale defined as

$$L' = \frac{\alpha T_m}{g} \frac{u_*^2}{k^2 T_*}$$

T_m and g in the above equation are the mean temperature averaged over a temperature profile, in absolute temperature scale, and the gravitational acceleration, respectively. The power of ζ , n , in Eqs. (1) and (2) should depend largely on thermal stability. It can be determined by means of the regression theory and least squares method of fitting data. When data points are closely spaced and the velocity and temperature gradients in the vertical direction can be assumed to be approximately equal to the ratios of finite differences of velocities and temperatures to that of height, respectively, n can be determined by the following linear regression equations:

$$\ln \frac{U_{i+1}-U_i}{Z_{i+1}-Z_i} = (n-1)\ \ln \frac{Z_{i+1}+Z_i}{2} + \ln \frac{\beta' u_*}{k(L')^n} \tag{3}$$

and

$$\ln \frac{T_{i+1}-T_i}{Z_{i+1}-Z_i} = (n-1)\ \ln \frac{Z_{i+1}+Z_i}{2} + \ln \frac{\gamma' T_*}{\alpha(L')^n} \tag{4}$$

where $1 \leq i \leq N-1$ and N is the number of data points in a profile. If similarity between the velocity and the temperature profiles does not exist then n will assume n_1 and n_2

The friction velocity and heat flux are not always measured. Therefore, the dimensionless wind shear , ϕ , and the lapse rate , ψ , may be defined as

$$\phi = \frac{Z}{U_m} \ \frac{\partial U}{\partial Z} \tag{5}$$

and

$$\psi = \frac{Z}{T_m} \frac{\partial T}{\partial Z} \qquad (6)$$

where the subscript m refers to the mean values. ϕ and ψ are similar in form to S and R, respectively. Substitution of Eq. (1) into Eq. (5) yields:

$$\phi = \frac{\beta' u_*}{k(L')^{n_1} U_m} Z^{n_1} \qquad (7)$$

Similarly,

$$\psi = \frac{\gamma' T_*}{\alpha L'^{n_2} T_m} Z^{n_2} \qquad (8)$$

The products such as $\beta' u_*/k(L')^{n_1}$ and $\gamma' T_*/\alpha(L')^{n_2}$ are determined from Eqs. (3) and (4), respectively.

Deacon numbers are defined as

$$\text{DEF} = -\frac{d(\ln\frac{\partial U}{\partial Z})}{d(\ln Z)} = 1 - \frac{d(\ln \phi)}{d(\ln Z)} \quad , \qquad (9)$$

and

$$\text{DEP} = -\frac{d(\ln|\frac{\partial T}{\partial Z}|)}{d(\ln Z)} = 1 - \frac{d(\ln \psi)}{d(\ln Z)} \quad . \qquad (10)$$

When Eqs. (7) and (8) are inserted into the respective Eqs. (9) and (10), the following equations will be obtained:

$$\text{DEF} = 1 - n_1 \quad ,$$

and

$$DEP = 1 - n_2 \quad .$$

The above equations explicitly imply that Deacon numbers defined in Eqs. (9) and (10) are only linearly dependent on the powers of Z which are characteristics of the diabatic wind and temperature profiles expressed in a power profile. If the similarity theory holds, then two Deacon numbers will become identical.

The relative rate of change of Richardson number can be shown to be related to the Deacon numbers in the following form:

$$\frac{dRi}{Ri} = (2DEF - DEP)\ \frac{dZ}{Z} - \frac{dT}{T} \quad .$$

The above equation may be rewritten as:

$$\frac{dRi/Ri}{dZ/Z} = 2\ DEF - DEP - \frac{dT/T}{dZ/Z} \qquad (11)$$

Using the finite difference approximation, the relative rate of change of Richardson number, mean wind temperature, and height of the data points can be calculated.

EXPERIMENTAL RESULTS AND DISCUSSION

Mean wind velocity and temperature profiles in a wind-tunnel boundary layer over a horizontal flat plate which was cooled or heated depending on whether inversion of lapse condition was desired were measured and reported by Chuang and Cermak (7). Data taken at an equidistance of 0.7 cm. for heights from 0.5 cm. up to 8.2 cm. were fitted to the log-plus-linear law and were shown to have some scatter by the authors (8). The same data were also fitted to the power law profiles by means of Eqs. (3) and (4) and the respective powers of Z, n_1 and n_2 , for the velocity and the temperature profiles which were determined by the least squares method. The products, $\beta' u_*/k(L')^{n_1}$ and $\gamma' T_*/\alpha(L')^{n_2}$, were evaluated in the same process. Eqs. (1) and (2) were rewritten as :

$$\frac{U-U_m}{U_m} = \frac{\beta' u_*}{n_1 k(L')^{n_1} U_m} \left[Z^{n_1} - \frac{1}{N} \sum_{i=1}^{N} Z_i^{n_1}\right] ,$$

and

$$\frac{T-T_m}{T_m} = \frac{\gamma' T_*}{n_2 \alpha (L')^{n_2} T_m} \left[Z^{n_2} - \frac{1}{N} \sum_{i=1}^{N} Z_i^{n_2}\right] .$$

Figs. 1 and 2 show both the Project Prairie Grass (9) and the wind tunnel data. The dimensionless velocity profiles shown in Fig. 1 and the dimensionless temperature profiles shown in Fig. 2 are better fitted than those of log-plus-linear profiles.

The dimensionless wind shear and lapse rate defined by Eqs. (5) and (6) were computed by means of finite differences. Eqs. (7) and (8) were plotted in Figs. 3 and 4, respectively. Both the laboratory and the field data conform to the theoretical lines quite well.

The Deacon numbers defined by Eqs. (9) and (10) were also computed by means of finite differences. These Deacon numbers can not be calculated very accurately, for they are the second order derivatives of the mean wind velocity and the mean temperature profiles with respect to height, Z. Theoretically, they are linearly proportional to the respective powers of Z for the mean velocity and the mean temperature profiles. In other words, the Deacon numbers should be constants for given profiles of the mean velocity and the mean temperature. Average Deacon numbers versus the powers of Z were plotted in Fig. 5.

The power for wind and temperature profiles n_1 and n_2 should be dependent only upon the thermal stability, Ri. Since Richardson number varies with height, a bulk Richardson number, $(Ri)_a$ defined as the average value of it over the whole range of the profile is a better representative stability of the flow field. Figs. 6 and 7 show n_1 and n_2 versus $(Ri)_a$ respectively. Although there are some degrees of scatter, they certainly reveal the functional dependence of n_1 and n_2 on the bulk thermal stability.

Moreover, n_1 and n_2 have almost the same dependence on $(Ri)_a$, in accordance with the similarity hypothesis pertaining to the mean velocity and the mean temperature profiles. It is also remembered that, in free convection, the power is minus one-third.

In examining Eq. (11), it is obvious that the relative rate of change of Richardson number is linearly proportional to the Deacon numbers provided that the relative rate of change of temperature is negligible. Figure 8 shows that the last term on the right hand side of Eq. (11) is indeed neglible. Therefore, Richardson number at height Z is given by:

$$Ri = (Ri)_o \left(\frac{Z}{Z_o} \right) \quad 2\,\mathrm{DEF}-\mathrm{DEP} \; ,$$

where $(Ri)_o$ is a Richardson number at Z_o .

CONCLUSIONS

Even though the log-linear model can describe the wind and temperature profiles in thermally stratified shear flows for all thermal stability, the power profile can yield a more accurate description of the profiles once the power, n is given. Unfortunately, however, the power of a profile is generally not known. The power was shown to be a function of the bulk Richardson number. More data are needed to determine this functional dependence. Nevertheless, this study shows that the power of wind and temperature profiles is not independent of the thermal stability.

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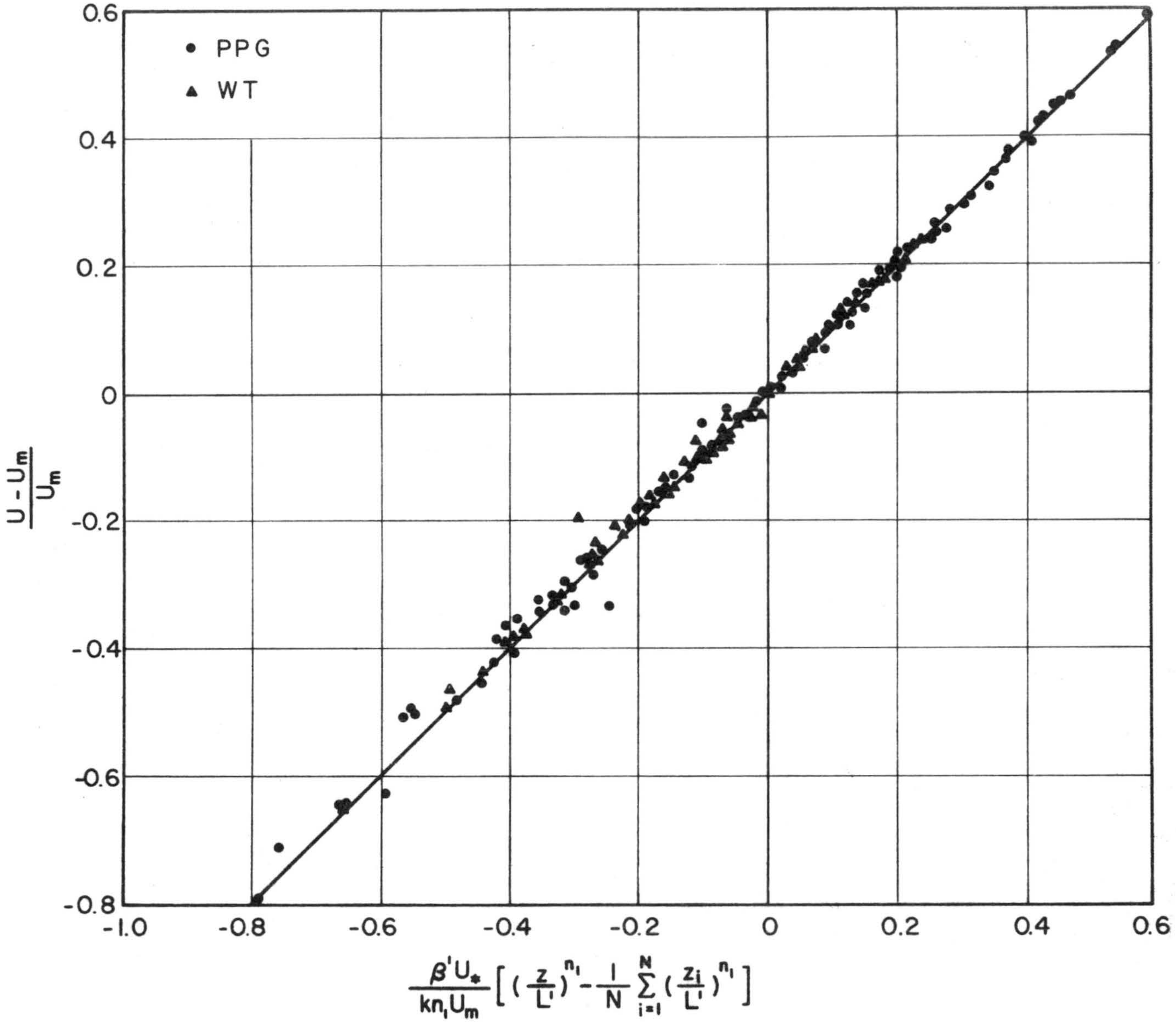
LIST OF SYMBOLS

Symbol	Definition
c_p	Specific heat of air at constant pressure, calories/$^\circ$C/gm
g	Gravitational acceleration, cm/sec^2
H	Heat flux in the vertical direction, calories/cm^2/sec
k	von Karman constant
K_h	Eddy thermal conductivity, cm^2/sec
K_m	Eddy viscosity, cm^2/sec
L	Monin-Obukhov length scale, $L'=\alpha L$, cm
n	Rational number
N	Total number of data collected in a profile
R	Dimensionless lapse rate
Ri	Richardson number
S	Dimensionless wind shear
T	Mean absolute temperature, $^\circ$K
T_*	$-H/(c_p \rho k u_*)$, friction temperature, $^\circ$C
u_*	Friction velocity, cm/sec
U	Local mean velocity, cm/sec
Z	Height, cm
α	K_h/K_m
β'	Arbitrary constant
γ'	Arbitrary constant
ζ	Z/L, demensionless height
ρ	Density of air, gm/cm^3
ϕ	Defined in Eq. (5)

LIST OF SYMBOLS (Continued)

Symbol	Definition
ψ	Defined in Eq. (6)
$(\ )_i$	The variable at height Z_i
$(\ )_m$	Mean value averaged over the profile
$(\ )_o$	The variable at height Z_o, an equivalent roughness height.

LIST OF FIGURES



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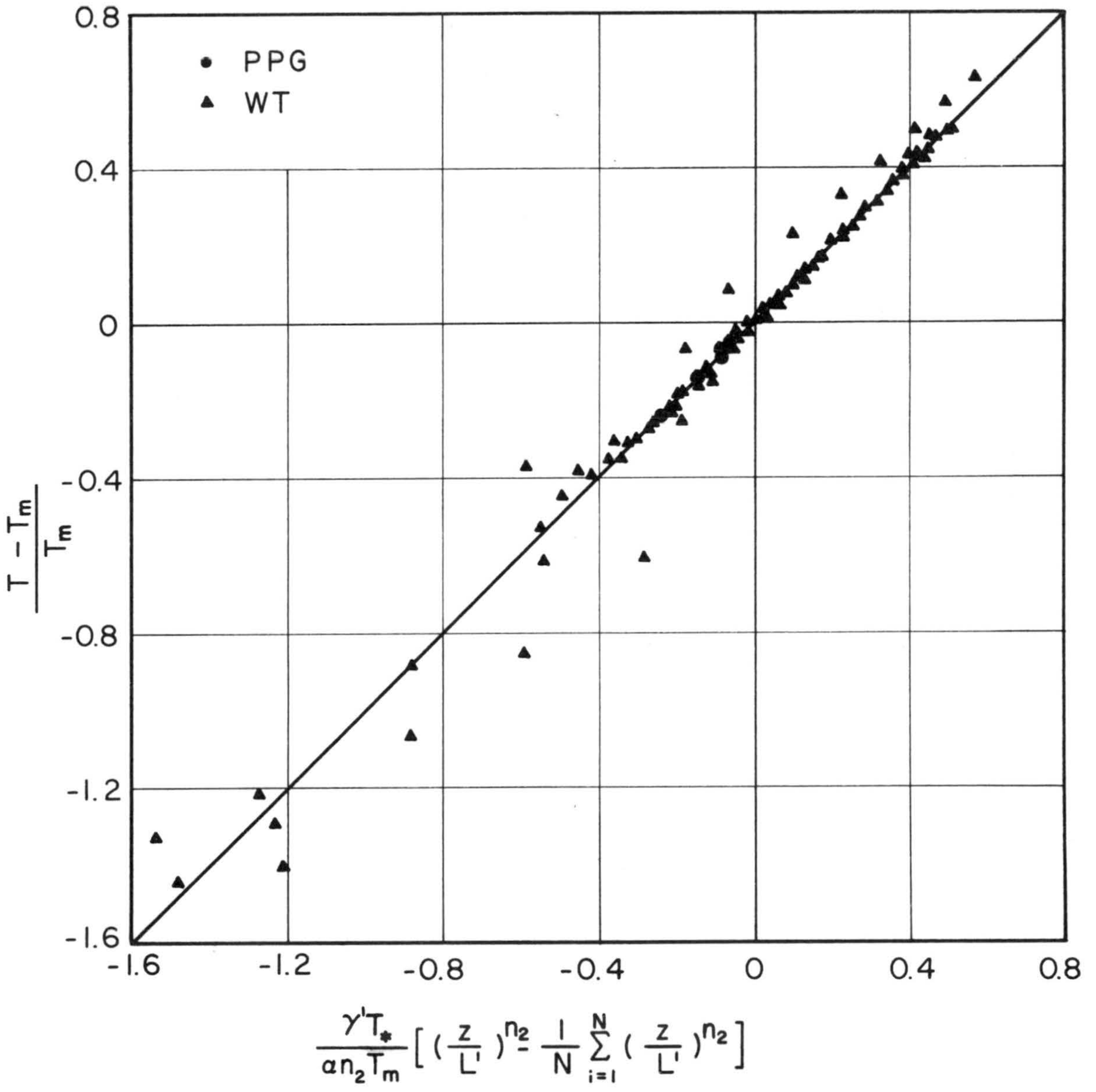


Fig. 2. Power law profile of the mean temperature

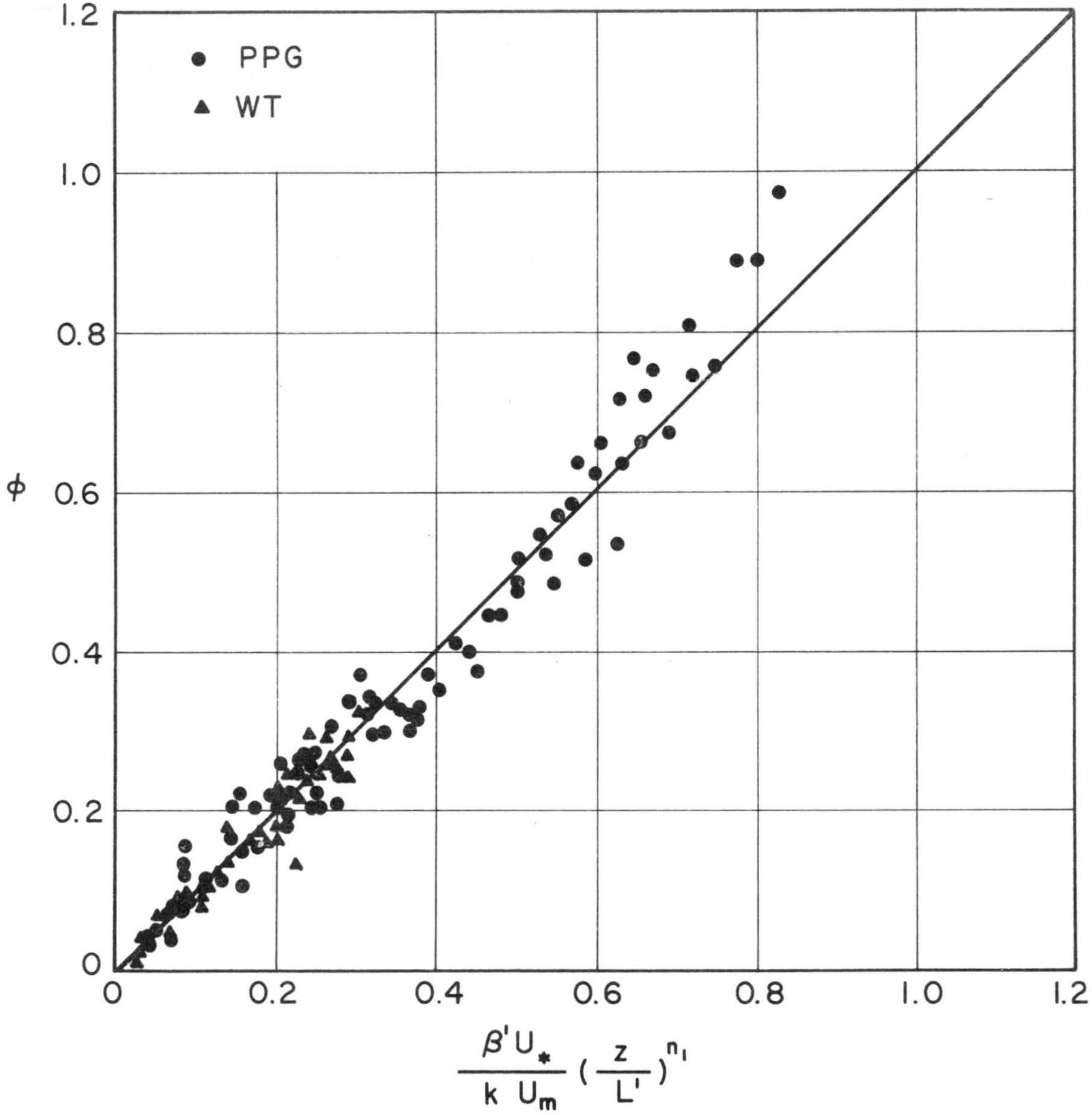
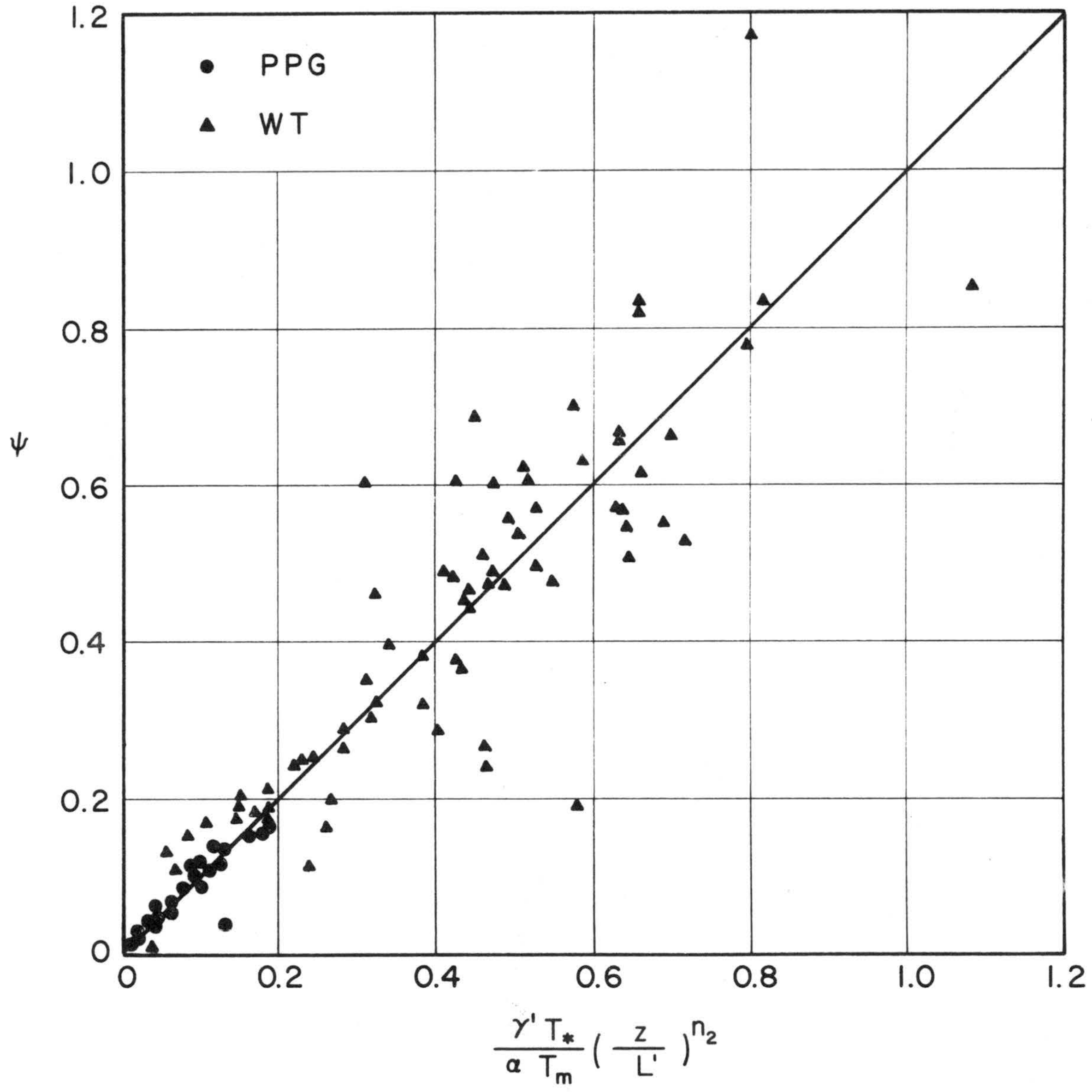


Fig. 3. Distribution of the dimensionless wind shear in thermally stratified shear flows



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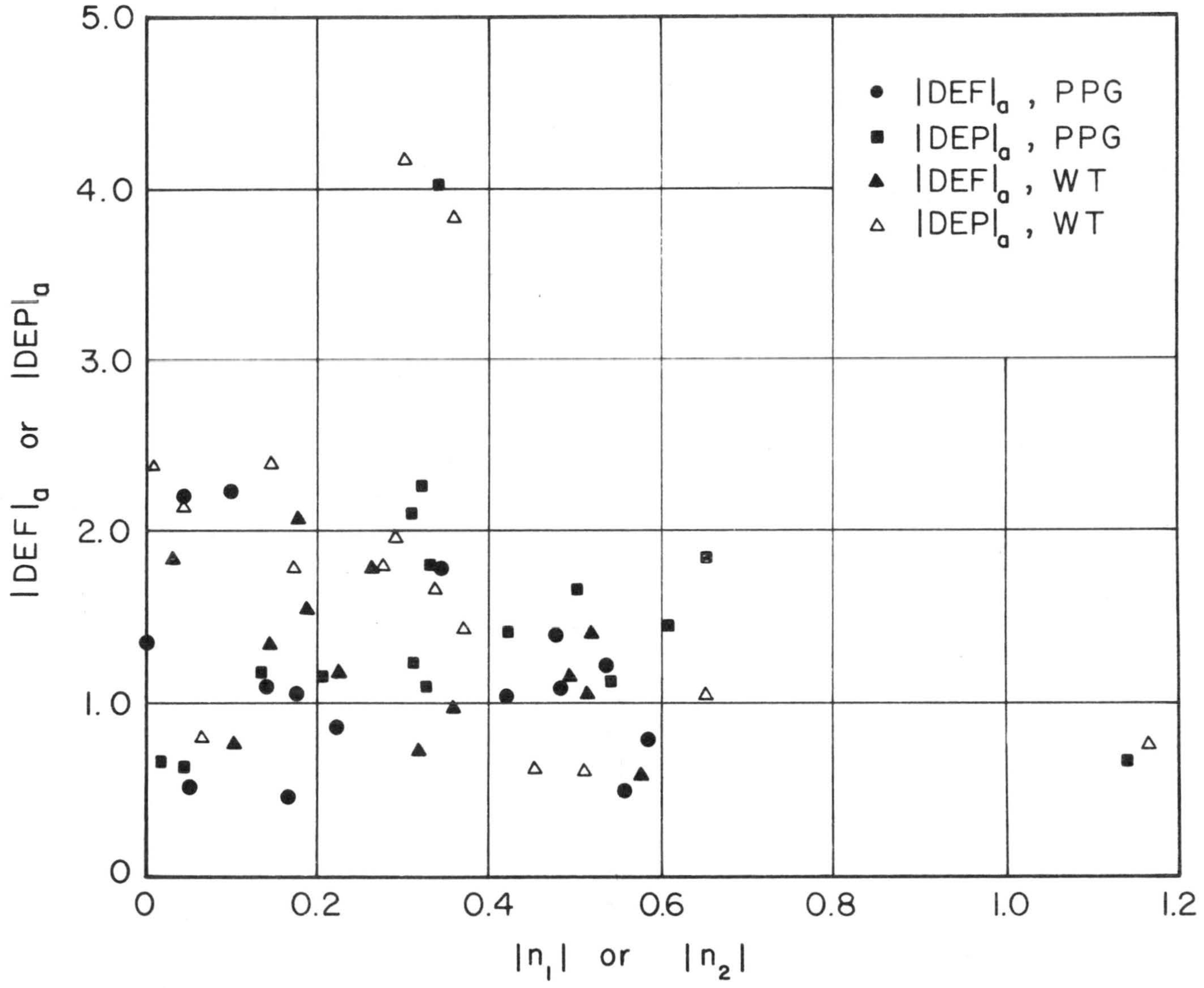

Fig. 5. Average Deacon numbers versus the power n_1 and n_2

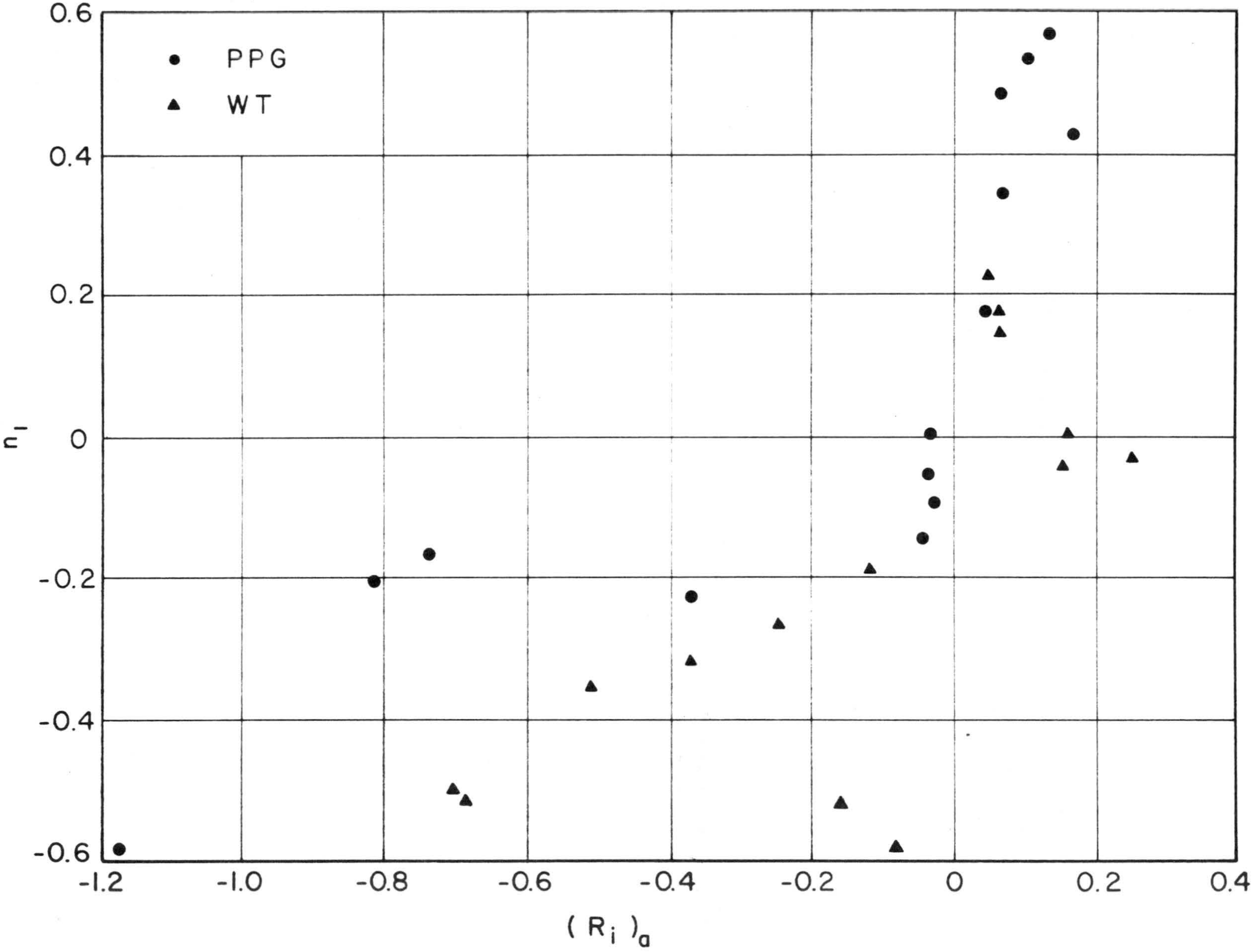

Fig. 6. Dependence of the power of mean velocity profiles on Richardson number

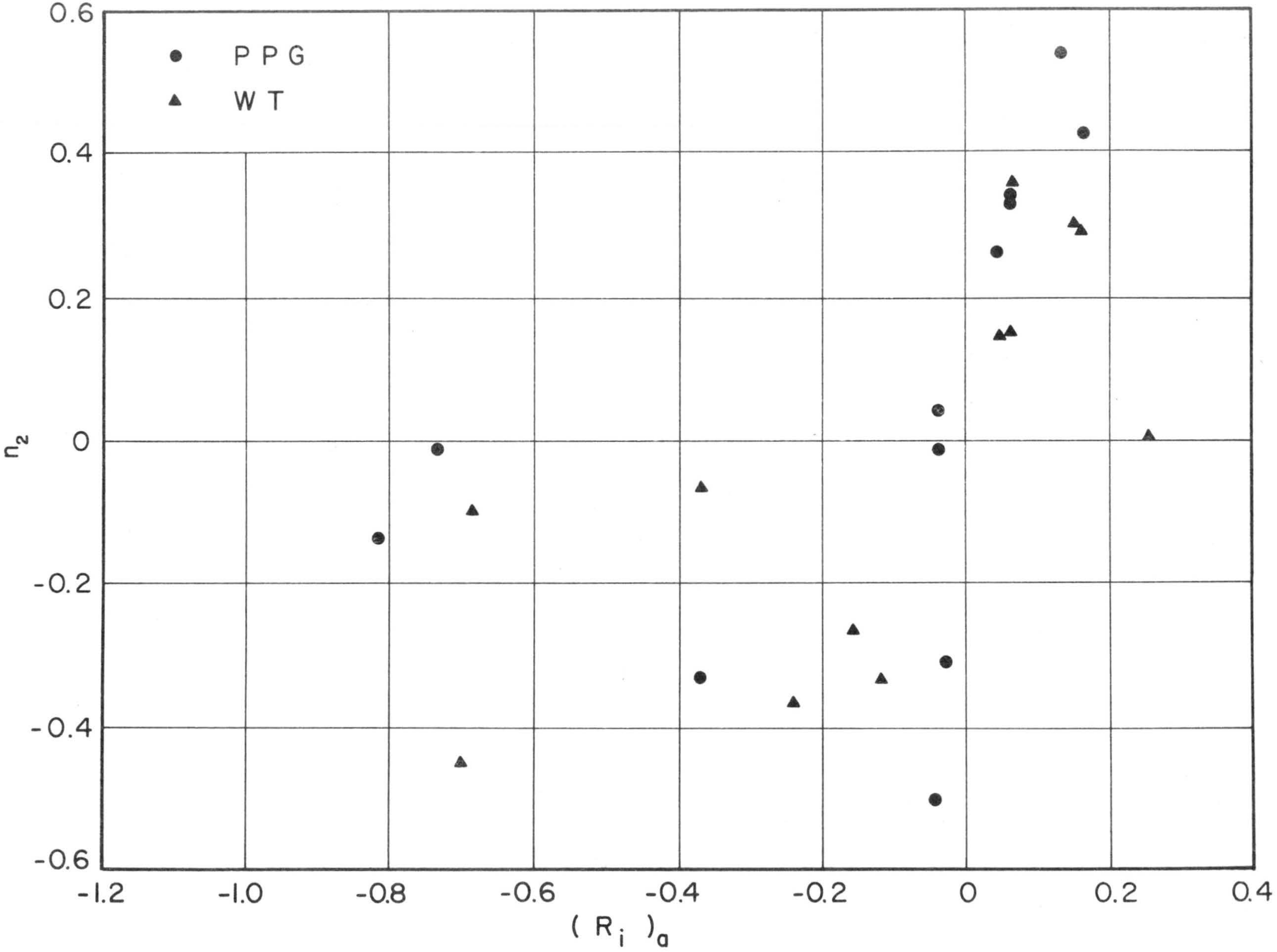

Fig. 7. Dependence of the power of mean temperature profiles on Richardson number

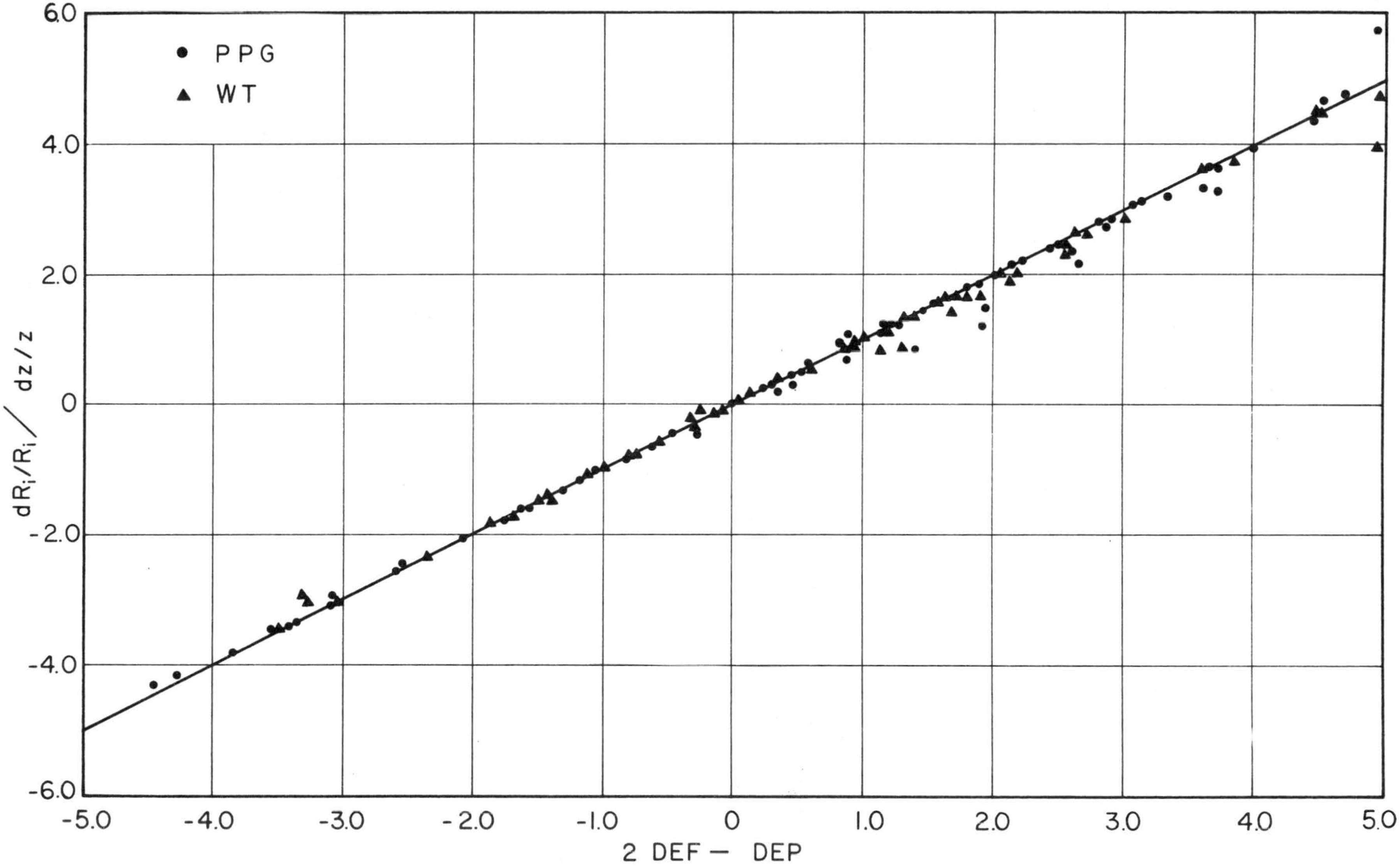

Fig. 8. Relative rate of change of Richardson number in terms of Deacon numbers

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