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**Thermal Gap Conductance of Conforming Surfaces
in Contact, Part II: Experimental Results**

by

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ABSTRACT

The results of a set of gap conductance experiments for bead-blasted surfaces are presented. Experiments were performed for a number of Stainless Steel 304 pairs and Nickel 200 pairs over a rms roughness range of 1.53 to 11.8 μm . Three different types of gases, helium, argon and nitrogen, were employed as the interstitial fluid, and the gas pressure was varied over 10 to 700 *torr*. The comparison between the measured and the predicted values shows excellent agreement.

KEYWORDS

gap conductance, contact resistance, contact interface

NOMENCLATURE

A_a	apparent area of contact
CLA	centerline average surface roughness
G	dimensionless gap resistance, $\frac{k_g}{h_g Y}$
h	conductance, $h = \frac{Q/A_a}{\Delta T}$
Kn	Knudsen number, Λ/Y
k_g	thermal conductivity of gas
M	gas parameter, $(\frac{2-TAC_1}{TAC_1} + \frac{2-TAC_2}{TAC_2})\beta\Lambda$
M^*	gas rarefaction parameter, M/Y
P	apparent contact pressure
P_g	gas pressure
Pr	Prandtl number, $c_p\mu/k$
R_p	maximum peak height
T	temperature
TAC	thermal accommodation coefficient
ΔT	effective temperature difference across interface, $T_1 - T_2$
Q	heat transfer rate
q	heat flux
Y	mean plane separation, effective gap thickness

Greek Symbols

γ	ratio of specific heats, c_p/c_v
Λ	molecular mean free path
Λ_0	Λ at reference temperature and pressure
σ	rms surface roughness

Subscripts

1, 2	surfaces 1 and 2
c	contact
g	gap
j	joint

1 INTRODUCTION

A number of experimental studies concerning interfacial gas heat transfer has been conducted over a period of several decades (Boeschoten and Van Der Held, [1]; Ross and Stoute, [2]; Rapier, Jones and McIntosh, [3]; Sanderson, [4]; Popov and Krasnoborod'ko, [5]; and Garnier and Begej, [6]). These experimental studies involve various types of interstitial gases and contact surfaces over a wide range of gas pressure and surface roughness. Despite the large number, these experimental data, in general, are associated with large degree of uncertainties, and thus offer little assistance (other than providing qualitative insights) to the development of an accurate gap conductance model.

In the present work, accurate gap conductance measurements were obtained for interfaces formed by the contact of a rough bead-blasted surface and a smooth lapped surface. Helium, argon and nitrogen were used as the interstitial gases with Stainless Steel 304 pairs and Nickel 200 pairs. Contact pressure was maintained at a very low level ($0.4 - 0.6 \text{ MPa}$), so that the contribution of the contact conductance to the total (joint) conductance is small. Gas pressure was varied over 10 to 700 *torr* to study the effect of gas rarefaction on gap conductance.

2 EXPERIMENTAL PROGRAM

2.1 Test Apparatus

A pyrex bell jar and a base plate enclose the test column consisting of the heater block, the heat meter, the upper and lower test specimens, the heat sink, and the load cell. The gas pressure inside the chamber was controlled by the vacuum system which consisted of a mechanical pump connected in series with an oil diffusion pump. This system provided a vacuum level lower than 10^{-5} *torr*. A brass heater block with two pencil-type heaters provided the maximum combined power of 200 *W*. Cooling was accomplished with an aluminum cold plate which, in turn, was chilled by a closed loop thermo-bath. Axial load was applied to the test column via a lever system which was activated by a diaphragm type air cylinder. The mechanical load was measured by a calibrated load cell. A metal diaphragm type of gauge was used to measure the gas pressure inside the test chamber. The uncertainty associated with the gas pressure measurement was ± 0.5 *torr*. Temperature measurements were made with 30 gauge type 'T' copper-constantan thermocouples. Data acquisition and reduction were performed under the control of an IBM PC. The mechanical loads and the heater levels were adjusted through the computer.

2.2 Test Specimens and Gases

Test specimens of Stainless Steel 304 and Nickel 200 were prepared from commercial bars. The specimens were machined to cylindrical shape of 25 *mm* diameter and 45 *mm* long. For each specimen, six holes of 0.64 *mm* diameter and 2.5 *mm* deep were drilled for the thermocouples. These holes were located 5 *mm* apart with the first one 10 *mm* from the contact surface.

The contact surfaces were prepared by bead-blasting. Talysurf profilometer was used to measure various surface roughness parameters. The roughness parameters estimated from the profilometer

Table 1: Properties of Gases

gas	γ	Pr	Λ_0 (μm)
Helium	1.67	0.67	0.186
Argon	1.67	0.67	0.0666
Nitrogen	1.41	0.69	0.0628

Note: Λ_0 values (Kennard [7]) are at 288 K and 760 torr.

were as follows:

- σ = rms surface roughness
- CLA = centerline average roughness
- R_p = maximum peak height roughness

Typically, three to six traces were randomly selected, and the roughness parameters were measured over 1 cm trace lengths.

Three different types of gases, helium, argon and nitrogen, were used in the experiments. Thermal conductivity correlations used for the gases were as follows:

Helium

$$k_g(W/m \cdot K) = 0.145 + 3.24 \times 10^{-4}T(^{\circ}C) \quad \text{for } 27 \leq T \leq 400^{\circ}C \quad (1)$$

Argon

$$k_g(W/m \cdot K) = 0.0171 + 4.05 \times 10^{-5}T(^{\circ}C) \quad \text{for } 20 \leq T \leq 400^{\circ}C \quad (2)$$

Nitrogen

$$k_g(W/m \cdot K) = 0.0250 + 5.84 \times 10^{-5}T(^{\circ}C) \quad \text{for } 27 \leq T \leq 400^{\circ}C \quad (3)$$

The thermal conductivity expressions for helium and nitrogen are the correlations of Hegazy [8], and for argon the tabulated values of Gandhi and Saxena [9] were correlated by the first author.

The values of other relevant properties of the gases (ratio of specific heats, Prandtl number and molecular mean free path) are shown in Table 1.

2.3 Experimental Procedures

Specimen placement

For the stainless steel tests, two specimens, one with smooth and the other with bead-blasted surfaces, were employed for each test. Always, the specimen with the bead-blasted surface was placed on top of the smooth-surface specimen.

For the nickel tests, an Armco iron heat meter was placed underneath the smooth-surfaced specimen in order to raise the mean interface contact temperature to the level compatible to that

of the stainless steel tests. The placement of the Armco iron also provided means to confirm correct measurement of heat flow rates through the upper and lower specimens.

The test column was shielded with aluminum foil, and insulated with about 2 cm thick layer of Quartz Wool, which was then covered again with aluminum foil.

Test Order

All tests under gas environment (helium, argon, and nitrogen) were preceded by at least one measurement under vacuum.

In general, the tests were performed in the following order:

- a) at least one vacuum test
- b) series of helium tests at various gas pressure
- c) vacuum test
- d) series of nitrogen tests
- e) vacuum test
- f) series of argon tests

Occasionally, different permutations of the above test orders were tried, so that any possible effect on gap conductance of the test order for the different gases may be observed.

Joint Conductance Measurements

The joint conductance h_j was obtained from the temperature measurements of the specimens according to its usual definition:

$$h_j = \frac{Q/A_a}{\Delta T} \quad (4)$$

The heat flow rate Q was taken as the average value of the heat flow rates of the upper and lower specimens. The interface temperature difference ΔT was obtained from the difference in the extrapolated values of the temperature of the interface from least-square fitted temperature distributions within the two specimens.

The time duration between the establishment of the control parameters (gas pressure, load level, and heater level) and the measurement was typically 30 - 120 minutes. In the case of 'cold' starts, at least three hours of elapse time were allowed before the first measurement.

Before each measurement was made, the change with time of joint conductance and the temperature readings from the thermocouples were closely monitored.

2.4 Experimental Uncertainty

The error associated with the joint conductance measurement (Eq. 4) is attributed mainly to the uncertainty in the estimate of the heat flow rate Q across the contact interface. The heat loss, as estimated by the difference between the heat flow rates through the upper and the lower specimens, was as great as 21 percent of the mean value for the tests with helium as the interstitial gas. The heat loss for the tests with nitrogen was much less (maximum 11 percent), and was the least with argon (maximum 8 percent). The mean value of the heat flow rates between the upper and the lower specimens was used as the estimate for Q in the present work, and this implies that the

maximum uncertainty associated with h_j measurement is estimated to be less than 10 percent for the tests with helium, 6 percent with nitrogen and 4 percent with argon. For vacuum tests the heat loss was in general less than 5 percent, and thus the uncertainty in the measured values of $(h_j)_{vacuum}$ (or h_c) is estimated to be less than about 3 percent.

The radiation heat exchange across the contact interface is estimated to be less than 1 percent of the total heat flow rate. The radiative component of the joint conductance, estimated by assuming two isothermal parallel plates (T_1 and T_2), diffusive grey surfaces with emissivities $\epsilon_1 = \epsilon_2 = 0.2$, is about 0.9 percent for the case of the lowest h_j measurement under a vacuum.

3 EXPERIMENTAL RESULTS

3.1 General Comments

Gap conductance measurements reported in the present work are based on the difference of the values of joint conductances obtained for the gas-environment and vacuum tests. In terms of the conductance coefficients, measured values of h_g correspond to the following:

$$(h_g)_{measured} = (h_j)_{gas} - (h_j)_{vacuum} \quad (5)$$

where $(h_j)_{gas} = h_j$ measurement in a gas environment
 $(h_j)_{vacuum} = h_j$ measurement in a vacuum

This is the most common means by which experimental values of h_g are estimated. The values of h_g obtained according to Eq. 5 most accurately reflect the actual values of h_g when the contribution of the heat transfer through the contacting solid spots is small compared to that through the gas layer.

Throughout this work, measured values of h_g will refer to the values obtained according to Eq. 5.

The effective gap thickness Y was estimated by the maximum peak height R_p of the rougher surface of each specimen pair (Song, Yovanovich and Goodman [10]). The effective Knudsen number, for the gap heat transfer, was estimated as:

$$Kn = \frac{\Lambda}{R_p} \quad (6)$$

The gap conductance prediction is based on the simplified expression (Song [11]) of the Integral model of Yovanovich, DeVaal and Hegazy [12] with Y/σ estimated as R_p/σ :

$$h_g = \frac{k_g}{f + M^*} \quad (7)$$

where $f = 1 + \frac{0.304}{(R_p/\sigma)(1+M/R_p)} - \frac{2.29}{[(R_p/\sigma)(1+M/R_p)]^2}$
 $M = \left(\frac{2-TAC_1}{TAC_1} + \frac{2-TAC_2}{TAC_2} \right) \left(\frac{2\gamma}{\gamma+1} \right) \left(\frac{1}{Pr} \right) \Lambda$
 $TAC_1, TAC_2 =$ thermal accommodation coefficients corresponding to the gas-solid combination of surface 1 and 2, respectively
 $\gamma =$ ratio of specific heats
 $Pr =$ Prandtl number
 $\Lambda =$ molecular mean free path

The ranges of the test parameters covered by all light-load tests are shown in Table 2.

The measured and predicted values of gap conductances are presented in terms of dimensionless parameters defined as (Song, Yovanovich and Goodman [10]):

$$G = \frac{k_g}{h_g R_p} \quad (8)$$

$$M^* = \frac{M}{R_p} \quad (9)$$

The values of TAC for He , Ar and N_2 were estimated according to a method proposed by Song [11]. The estimated values of TAC are 0.55, 0.90 and 0.78 for He , Ar and N_2 , respectively.

3.2 Experimental Results

Stainless Steel 304 Pair Experiments

The roughness of the bead-blasted surface for Exp. # 1 ($\sigma = 1.53 \mu m$) is the lowest of all bead-blasted surfaces. Due to the low combined roughness of the surface pair the effective gap thickness, Y , as low as $5.6 \mu m$ was obtained. Thus, it was possible to achieve a high degree of gas rarefaction (Knudsen number as high as 4.2 for the helium test at $P_g = 9.4 \text{ torr}$). When the results of all helium, argon and nitrogen tests are combined, the gap conductance tests for this sample pair span a wide Knudsen number range, $0.019 < Kn < 4.2$, which nearly covers the continuum, temperature-jump, and transition heat conduction regimes. Figure 1 shows the comparison between the measured and the predicted values of the gap conductances in the form of the dimensionless resistance G over a range of the rarefaction parameter M^* . It is observed from the figure that in terms of the two dimensionless parameters M^* and G , the test results for the three gases essentially form a single curve and there is no longer the need to distinguish between different gases. The test results of this specimen pair combined with the three different gases cover three orders of magnitude range of the rarefaction parameter M^* , and for this range, the measured values of the gap conductances (or G) agree well with the predicted values.

The Knudsen number range covered by Exp. # 2 ($\sigma = 4.83 \mu m$) is $0.0078 < Kn < 1.6$, whose lower end would be considered to be well within the continuum regime. The dimensionless gap resistance results are shown in Fig 2.

Nickel 200 Pair Experiments

The thermal conductivity of nickel is about 3.5 (at $170^\circ C$) times that of stainless steel. Thus the contribution to the joint conductance of the contact conductance is significantly greater than that of the stainless steel contact of similar conditions. The ratio of measured values of the joint

Table 2: Ranges of Parameters for Light-Load Experiments

Parameters	Exp. # 1	Exp. # 2	Exp. # 3	Exp. # 4
specimens	SS 304	SS 304	Ni 200	Ni 200
σ (μm)	1.53	4.83	2.32	11.8
R_p (μm)	5.55	14.7	8.61	30.6
R_p/σ	3.63	3.04	3.71	2.59
h_c ($W/m^2 \cdot ^\circ C$)	452 ± 25	241 ± 3	1130 ± 30	725 ± 30
h_g ($W/m^2 \cdot ^\circ C$)	711 - 9660	460 - 5150	625 - 17900	417 - 7830
h_g/h_c	1.57 - 21.4	1.91 - 21.4	0.553 - 15.8	0.575 - 10.8
P_g (torr)	9.4 - 710.9	9.5 - 665.0	9.6 - 697.7	9.4 - 699.7
Kn	0.019 - 4.2	0.0078 - 1.6	0.013 - 2.6	0.0034 - 0.76
P (MPa)	0.60 ± 0.02	0.47 ± 0.02	0.52 ± 0.02	0.38 ± 0.01
T_c ($^\circ C$)	172 ± 4	168 ± 4	170 ± 3	172 ± 4
ΔT ($^\circ C$)	5.8 - 85.5	6.7 - 105.9	5.5 - 39.9	12.2 - 63.8
q (kW/m^2)	27.7 - 58.7	34.4 - 55.5	52.7 - 104.9	55.9 - 104.1

$$\sigma = \sqrt{\sigma_1 + \sigma_2}$$

and contact conductances varies from 0.65 for argon at 11 torr to 16.2 for helium at 640 torr. For both argon and nitrogen measurements, the contact conductance contributed at least 30 percent of the joint conductance. The gap conductance results are in excellent agreement as shown in Fig. 3. Even for the argon measurements at $P_g = 11$ torr ($M^* = 4.0$), where the gap conductance is approximately half of the contact conductance, the agreement is very good.

The surface roughness for Exp. # 4 ($\sigma = 11.8 \mu m$) is the highest of all bead-blasted surfaces. Because of the high value of σ (thus large Y), the lower-end of the Knudsen number range of the test is situated well within the continuum regime. The value of R_p/σ (and thus Y/σ estimate) for the sample pair is 2.59 (compared to 3.63, 3.04 and 3.71 for the samples in Exp. # 1 through 3, respectively). At this low level of Y/σ the effect on the gap conduction due to the non-uniformity of the local heat flow length becomes significant, and this experiment provides a test to verify the modelling of the surface roughness effect. The gap conductance results (Fig. 4) are in excellent agreement with the theory. The Knudsen number of the argon test at $P_g = 670$ torr ($M^* = 0.018$ in the figure) is 0.0034 and the corresponding heat-flow regime may be considered continuum. At this point the predicted and the measured values of G are in excellent agreement at 0.80. This seems to suggest that the enhancement in the gap conductance due to the non-uniformity of the local heat flow length (arising from the surface roughness) for the particular test surface pair is about 20 percent. Thus the surface roughness effect, as modelled by the present gap conductance theory, may be significant and should not be ignored.

SUMMARY

Gap conductance measurements for light contacts of Stainless Steel 304 pairs and Nickel 200 pairs with helium, argon and nitrogen as interstitial gases are presented. The measurements were obtained over wide ranges of surface roughness and gas pressure. The measured values of gap conductance are in excellent agreement with the predictions which use the roughness parameter R_p as the estimate for the light load effective gap thickness. It was also demonstrated that for a given contact interface geometry (i.e. specified roughness and mechanical load) the gap conductance measurements of various gases, when normalized to G , depend upon one parameter M^* .

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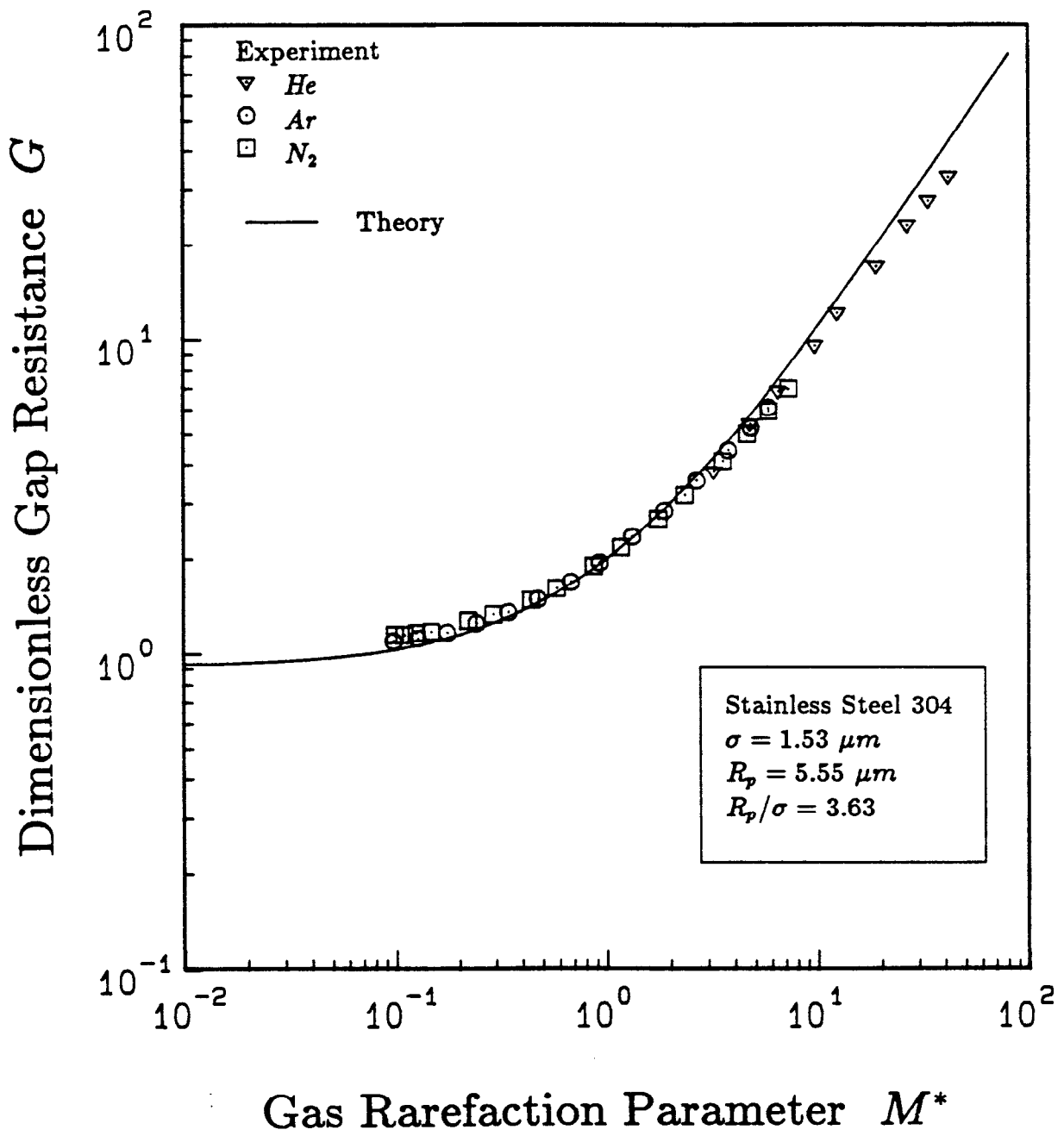


Figure 1: Dimensionless Gap Resistance Results for Exp. # 1

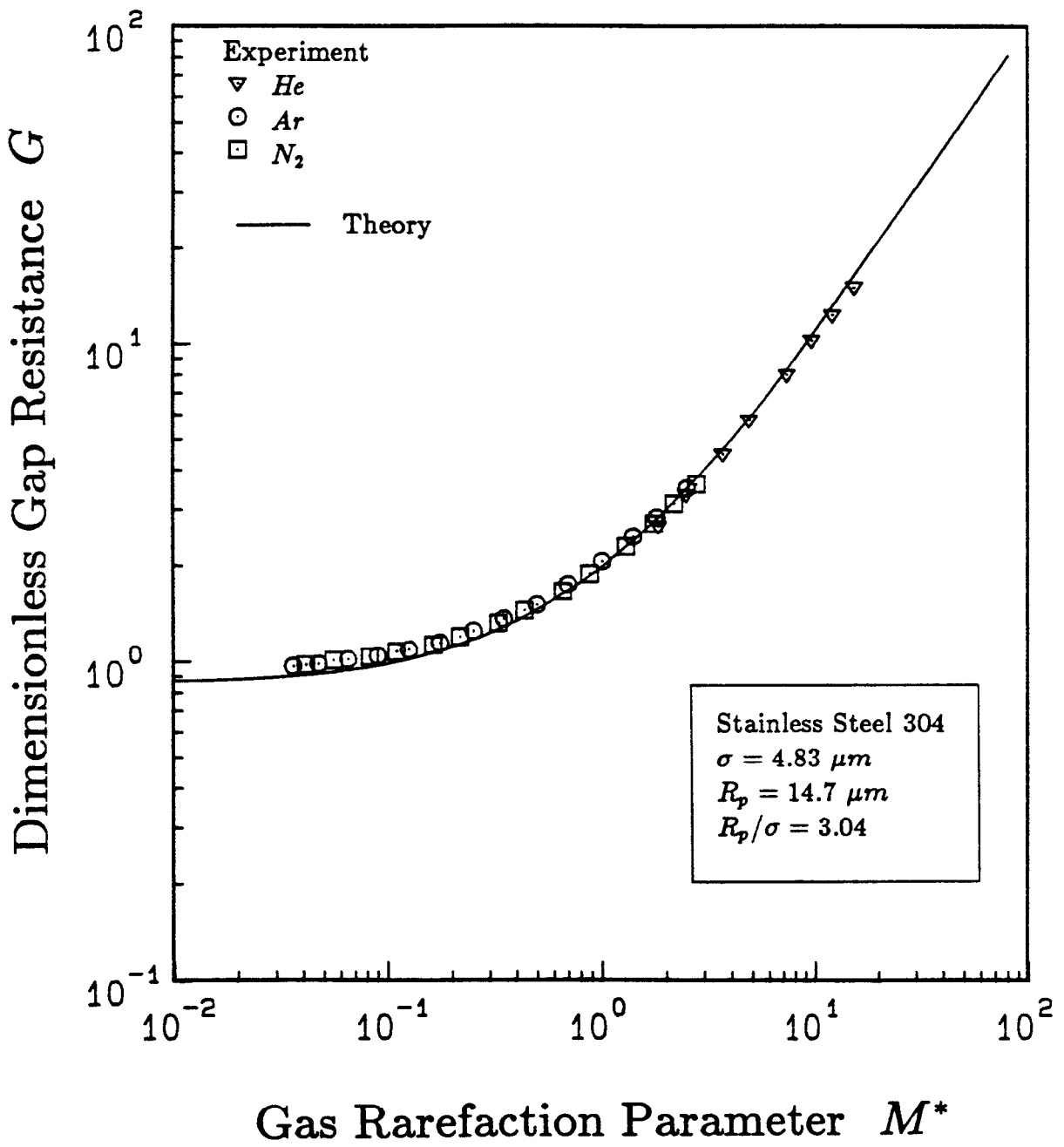


Figure 2: Dimensionless Gap Resistance Results for Exp. # 2

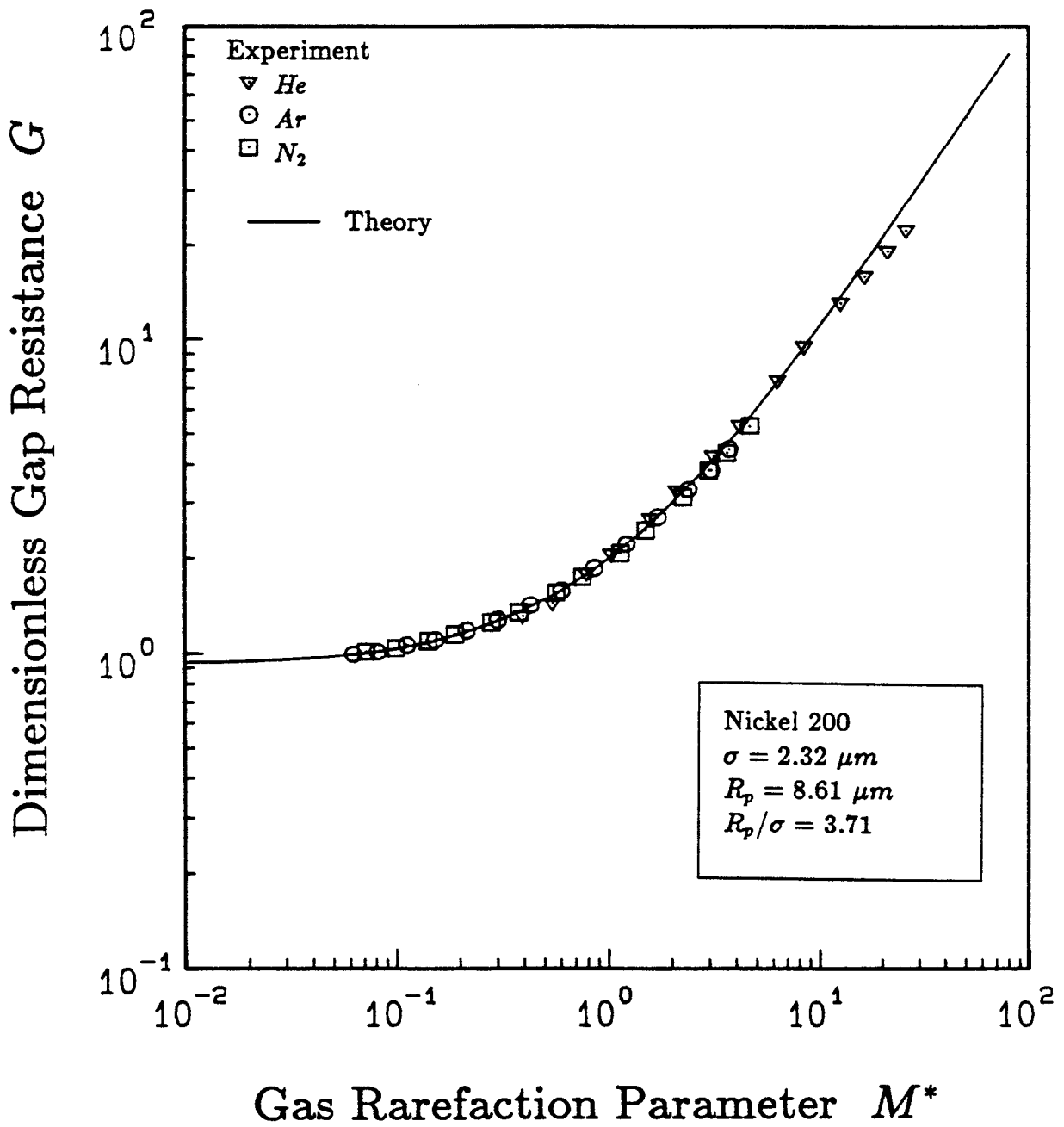


Figure 3: Dimensionless Gap Resistance Results for Exp. # 3

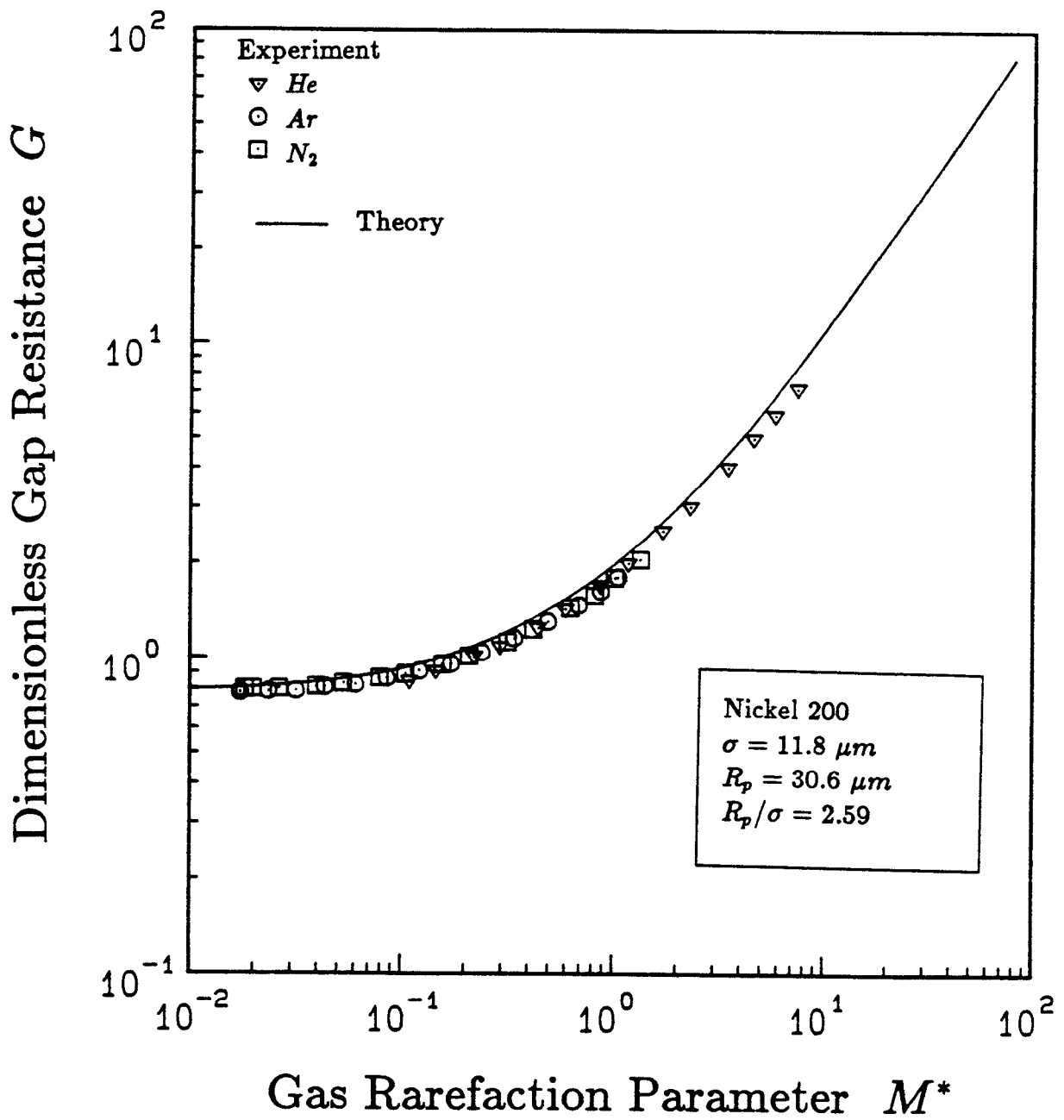


Figure 4: Dimensionless Gap Resistance Results for Exp. # 4