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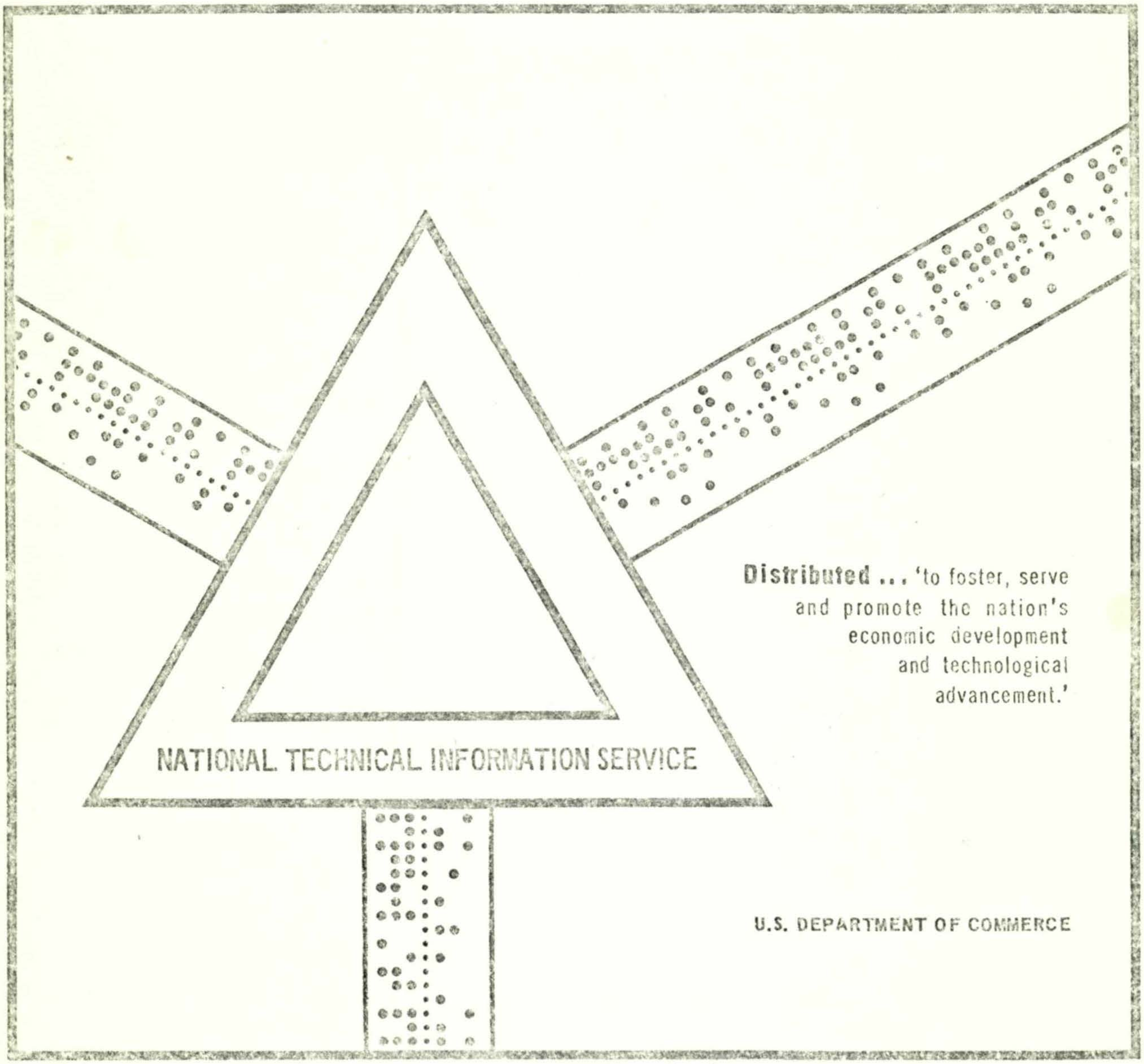
APPLICATION OF SCALING DATA TO MODEL TESTS TO OBTAIN FULL-SCALE RESULTS

Institute for Rapid Transit
Washington, D. C.

March 1971



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Interim Report

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Prepared by
AEROSPACE TECHNOLOGY
Division ~~of~~
DEVELOPMENTAL SCIENCES, INC.,
City of Industry, California

for

UNITED STATES DEPARTMENT OF TRANSPORTATION
Urban Mass Transportation Administration
Washington, D.C. 20590

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APPLICATION OF AERODYNAMIC SCALING DATA TO GEOMETRICALLY SCALED MODEL TESTS TO OBTAIN FULL-SCALE PREDICTIONS

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SUMMARY

The purpose of this document is to consider at the beginning of the Subway Environmental Research Project, the methodology for relating the experimental scale modeling data to full-scale predictions.

The similitude laws being developed at CIT/JPL are considered in terms of their application to the geometrically-scaled experiments to be run at DSI-AT. A procedure for scaling the DSI-AT data to full-scale is discussed and examples are given.

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OUTLINE OF THE SUBWAY ENVIRONMENTAL CONTROL EXPERIMENTAL PROGRAM

The following is a suggested procedure for the determination of the full scale vehicle aerodynamic and heat transfer parameters from simulated experimental data.

The experiments will be conducted by two groups·

Group (A) will be at the JPL/CALTECH Facility

Group (B) will be at the DSI-AT facility

GROUP "A" (JPL)

The experiments will be subdivided into the following parts:

A1. Steady State Aerodynamic experiments (Reynolds Number)

A2. Unsteady Aerodynamic Experiments (Mach Number)

A3. Heat Transfer Experiments (Similitude of braking heat)

This subdivision is possible due to the fact that the predominant parameters under consideration are separable, thus rendering the investigation of each parameter more simple and convenient.

Experiments at JPL will be carried out on ordinary cylindrical models with no detailed consideration made as to the scaling of specific vehicle geometry. However the physical scale will be exactly duplicated.

A1. Steady State Aerodynamic Experiments

The aim is to determine experimentally the Drag Coefficient "C_D" and the Velocity Ratio "β" for a wide range of Reynolds numbers "Re" including that of the full scale.

The following parameters will be held constant during an experiment:

a. The blockage ratio σ

b. The vehicle and tube length to diameter ratios $\frac{\ell}{d}$, $\frac{L}{D}$

c. The venting system parameters $C_{\dot{m}_s}$, $C_{\Delta p_s}$, λ_s, $\frac{A_s}{A}$, ε_s

d. The tube roughness parameters ε_t, λ_ε

e. The geometrical shape of the nose and tail

Other sets of C_D and β versus Re curves will be obtained for different values of the above listed parameters. From a theoretical similarity study carried out at Caltech the hope is to enable the grouping of some of these parameters so that a more universal Master Chart of C_d and β versus R_e could be obtained, i. e.,

$$C_D \phi \left(\sigma, \frac{\ell}{d}, \frac{L}{D}, C_{\dot{m}_s}, \varepsilon, \ldots\right) = f(R_e)$$

The most general functional ϕ is to be found if it exists.

For certain values of the parameters mentioned before, a curve C_j is obtained as shown in Fig. (1), for each of C_D and β. Such a curve could be fitted by a polynomial function with R_e as the only independent variable, i. e., the function $f(R_e)$ is fitted. This functional relationship will be useful later in obtaining the full scale C_D and β as programmed information when the detailed vehicle geometry is taken into consideration at the AT Facility.

A2. Unsteady Aerodynamic Experiments

a. Effect of Mach number and wave drag

Light weight models will be dropped at a certain fixed velocity and the C_D and β measured at different instantaneous scaled times τ. The C_D and β are then plotted versus the acceleration parameter ($\dot{v}d/v^2$) with Mach number as a fixed parameter. The experiment is repeated using different gases thus changing the Mach number. This change of Mach number will be accompanied with a change of pressure so that the Reynolds number should be kept constant.

A final reduction in the data leads to C_D and β curves versus the Mach number M with the acceleration parameter taken fixed for each curve. The result is shown in Fig. (2). The usefulness of this experiment will appear later in the determination of the C_D and β corrections due to the Mach number simulation at the AT unsteady experiments. One notes that the Mach number dependence in this experiment is of second order.

b. Effect of transient at tube entry from free atmosphere.

The Mach number is the important parameter and is of first order. The C_D and β are measured versus nondimensional scaled time τ for different Mach numbers M. This will lead to the C_D and β transient increments from entry in a tube.

In this experiment, the main measurement is the dynamic pressure at a convenient location in the nose of the vehicle.

A. 3 Heat Transfer Experiments

The purpose of these experiments is to determine the importance of the method of heat generation on the heat transfer parameters. Such information is essential in designing the heat generation system used later at the AT Facility. Resistor grids are the main heat generation source, one should like to simulate the breaking heat generated by these grids with the least complication, as long as the correct thermodynamic characteristics are obtained.

A theoretical study at Caltech is carried in parallel to these experiments to determine the important heat transfer parameters that are responsible for the generation, propagation and dissipation of the heat in the tube and stations. Such a study includes also the various similarity laws that govern the relations between the scaled model and full size vehicle parameters.

Models will be dropped in the tube with a hot spot attached to them at a convenient location. The rate of heat flow can be controlled by the current input. C_D and β will be measured when the model attains steady state for different values of the rate of heat transfer $\dot{q}$.

The experiment is repeated with the hot spot replaced by a circular flat plate emitting a rate of heat flow in the same range as with the hot spot experiment. The results are plotted in sets of two curves as shown in Fig. (3). The effectiveness of the geometry of the heat generator as a heat transfer parameter will be judged by whether or not the curve corresponding to the hot spot experiment coalesce with the curve corresponding to the circular plate experiment.

GROUP "B" (AT)

The experiments will be subdivided into the following parts:

B1. Steady State Aerodynamic Experiments

B2. Unsteady Aerodynamic Experiments

B3. Heat Transfer Experiments

Experiments at AT will be carried out using geometrically similar models but with different physical parameters, except the acceleration parameter ϕ which fortunately is the same for both full scale and model.

B1. Steady State Aerodynamic Experiments

C_d and β will be measured for a geometrically similar vehicle running at a speed up to 40 MPH. For specific values of the geometrical parameters mentioned in A1 the values of C_D and β will be measured for a particular R_e. A point p_1 (Fig. (1)) is then located on a C_D;β versus R_e chart obtained previously from JPL, for nearly the same values of the geometrical parameters in A1. For that particular value of R_e, a point p_2 can be located on the JPL curve which will have lower values of corresponding C_D and β. The discrepancy between the points p_1 and p_2 is due to the corrected geometry effect.

Assuming that the same functional relationship between C_D or β and R_e still holds, i. e., $f(R_e)$ has the same character, one can easily find the C_D and β corresponding to the full scale vehicle from the similarity relation: (Fig. (1))

$$\frac{(C_D)_a}{(C_D)_{\text{full scale}}} = \frac{(f(R_e))_{\text{model}}}{(f(R_e))_{\text{full scale}}} = \frac{(C_D)_{j2}}{(C_D)_{j3}}$$

A similar correspondence exists for β.

B2. Unsteady Aerodynamic Experiments

In the unsteady experiments, the geometrically similar model to be tested should have the same nondimensional acceleration parameter $(\dot{v}d/v^2)_{\text{model}} = (\dot{v}d/v^2)_{\text{full scale}}$

this implies $\dot{v}_{\text{model}} = (\dot{v}d/v^2)_{\text{full scale}} \dfrac{(v^2)_{\text{max model}}}{d_{\text{model}}}$

The C_D and β are then measured at different times in the acceleration/deceleration regimes and plotted against the scaled nondimensional time τ.

For each instantaneous value of the velocity, the corresponding R_e, C_D and β are found for the model. A similar procedure is adopted as the one previously used in the steady state case, for the determination of the full scale C_D and β at instantaneous times in the acceleration/deceleration regimes. A full scale C_D and β could thus be found at any instantaneous time (noting that time should be rescaled to full size once more).

B3. Heat Transfer Experiments

It is possible to get a temperature distribution in the model situation similar to that of the real case; however this would require a clever choice of wheel material and of the gas in the tube. Such a choice must satisfy a number of conditions for example

$$\left(\frac{t\ \eta_w}{d^2}\right)_m = \left(\frac{t\ \eta_w}{d^2}\right)_r$$

$$\left(\frac{\dot{v}\ d^3}{\eta_w^2}\right)_m = \left(\frac{\dot{v}\ d^3}{\eta_w^2}\right)_r$$

$$\left.\frac{k_w}{k_f}\right]_m = \left.\frac{k_w}{k_f}\right]_r$$

$$\left.\frac{\eta_w}{\eta_f}\right]_m = \left.\frac{\eta_w}{\eta_f}\right]_r$$

where an m subscript denotes the model, a w subscript denotes the properties of wheels, f denotes properties of the fluid, r denotes full scale.

$\dot{v}$ is train accel.

t is time

d is train diameter

k thermal conductivity

η thermal diffusivity

Since the fluid used in the model situation is air, then such previously mentioned arrangements cannot be made available. However assuming the wheels of the train are made of a material having a very small conductive resistance implies that the wheels are nearly at a uniform temperature. With such assumptions, a heat control system could be devised generating heat to the wheels such that it will cause the average air temperature at a certain cross section of the tube equal to the average temperature in the real situation.

Illustrative example on the determination of C_D and β for the full-scale vehicle from available scaled model data

I) Isothermal Steady-State Motion

Assume a model having certain geometrical tube and vehicle geometrical characteristics:

$$\chi = \chi\left[\sigma, \frac{\ell}{d}, \frac{L}{D}, \varepsilon, \ldots\right]$$

The C_{Dr} (full-scale drag coefficient) can be determined in the following steps:

1. The scaled model with similar geometry is tested at a prescribed velocity and the C_{Da} corresponding to some Re_a is measured.
2. A Caltech/JPL curve of C_D versus Re is chosen having nearly the same χ (geometrical parameters) fig. (1). A (Re, C_D) point is located on this chart (point p_1). The vertical line through Re_a crosses the JPL curve (incorrect geometry) at point p_2 to which corresponds a $C_D = C_{Dj2}$. Thus correction of C_D from considering the correct geometry is:

   $$(\Delta C_D)_g = C_{da} - C_{Dj2}$$

3. Since the model Re is different from that of the real vehicle, the C_D should be corrected by using the scaling law:

   $$\frac{C_{Dr}}{C_{Da}} = \frac{C_{Dj3}}{C_{Dj2}} \Longrightarrow C_{Dr} = C_{Da} \cdot \left(\frac{C_{Dj3}}{C_{Dj2}}\right)$$

   where C_{Dj3} is the C_D of a JPL model having $Re = Re_r$.

Thus the Re correction is

$$(C_D)_{Re} = C_{Da} - C_{Dr}$$

The full-scale drag coefficient can then be written in the form

$$C_{Dr} = C_{Dj2} + (\Delta C_D)_g - (\Delta C_D)Re$$

II. Isothermal Unsteady Motion

Assume the same model as in the steady-state motion experiments. The model is run at a prescribed velocity profile, i. e., at a prescribed constant acceleration $\dot{v}$ such that the acceleration parameter $\frac{\dot{v}d}{v^2}$ is kept the same for the model as for the full-scale vehicle. The C_{Dr} can be determined at any instantaneous position, i. e., at any time from the following procedure:

1. The C_{Da} of the geometrically similar vehicle is measured at the instantaneous Re_a.
2. A Caltech/JPL curve of C_D versus Re is chosen having nearly the same χ (geometrical parameters) fig. (4). A (Re, C_D) point is located on this chart (point p_1). The vertical line through Re_a crosses the JPL curve (incorrect geometry) at point p_2 to which corresponds a $C_D = C_{Dj2}$. Thus correction of C_D from considering the correct geometry is:

$$(\Delta C_D)_g = C_{da} - C_{Dj2}$$

3. Since the model Re is different from that of the real vehicle, the C_D should be corrected by using the scaling law:

$$\frac{C_{Dr1}}{C_{Da}} = \frac{C_{Dj3}}{C_{Dj2}} \Rightarrow C_{Dr1} = C_{Da} \cdot \left(\frac{C_{Dj3}}{C_{Dj2}}\right)$$

where C_{Dj3} is the C_D of a JPL model having $Re = Re_r$. Thus, the Re correction is

$$(C_D)_{Re} = C_{Da} - C_{Dr1}$$

The full-scale drag coefficient before the Mach number correction can then be written in the form:

$$C_{Dr1} = C_{Dj2} + (\Delta C_D)_g - (\Delta C_D)_{Re}$$

4. Finally since the model is running at a different Mach number from the full scale, a Mach number correction should be accounted for as follows:

   a - Let the model Mach number be M_a (based on maximum speed). Let the acceleration parameter be Φ_2. This locates a point on a curve with $\Phi = \Phi_2$ in Figure (2). Let the Mach number for the full-scale vehicle be M_r. Since $\Phi_m = \Phi_r$ then a second point on the same $\Phi = \Phi_2$ can be located in Fig. (2) corresponding to M_r. The Mach number correction is then:

$$(\Delta C_D)_M = C_{DrM} - C_{Da}$$

   b - Going back to Fig. (4), the C_{Dr} can be determined by increasing the C_{Dr1} by $(\Delta C_D)_M$ thus locating a final point p_5. C_{Dr} can thus be written as:

$$C_{Dr} = C_{Dj2} + (\Delta C_D)_g - (\Delta C_D)_{Re} + (\Delta C_D)_M$$

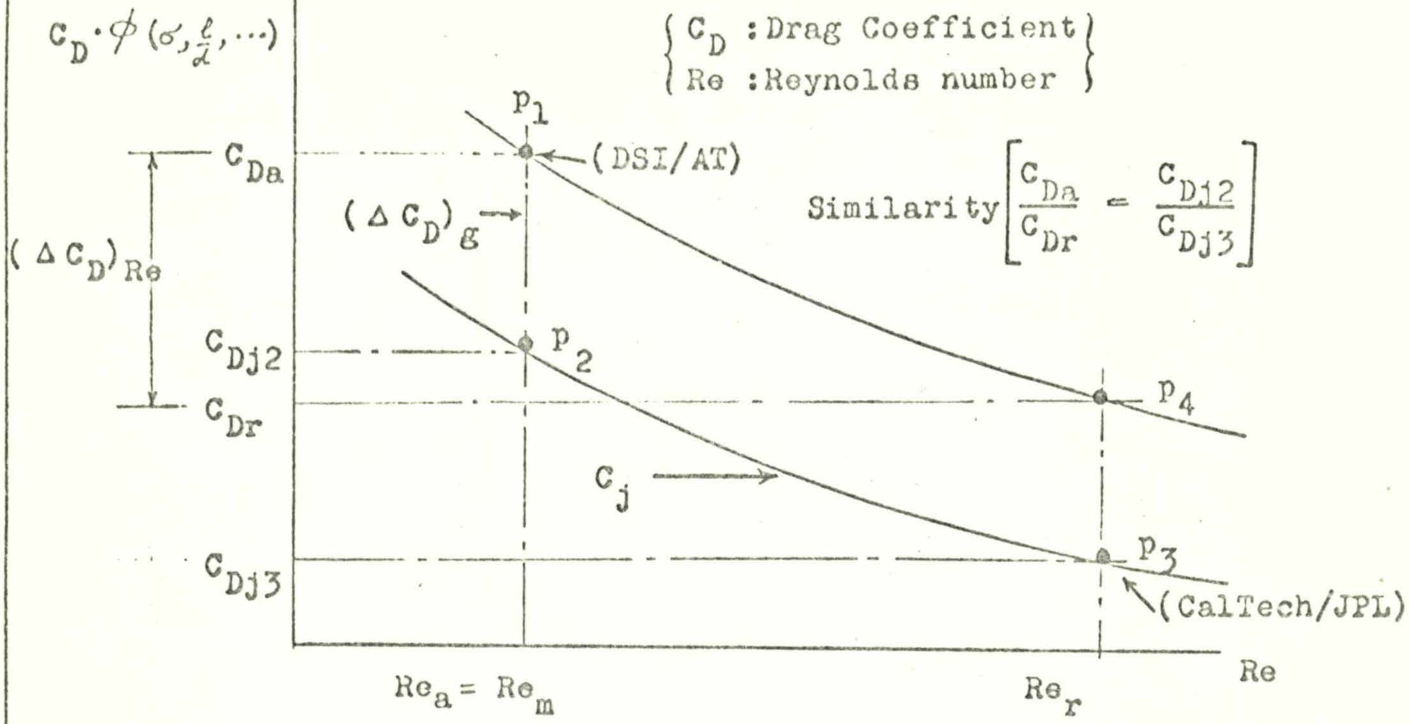

Figure (1)

Geometry & Reynolds Number Correction at Steady-State

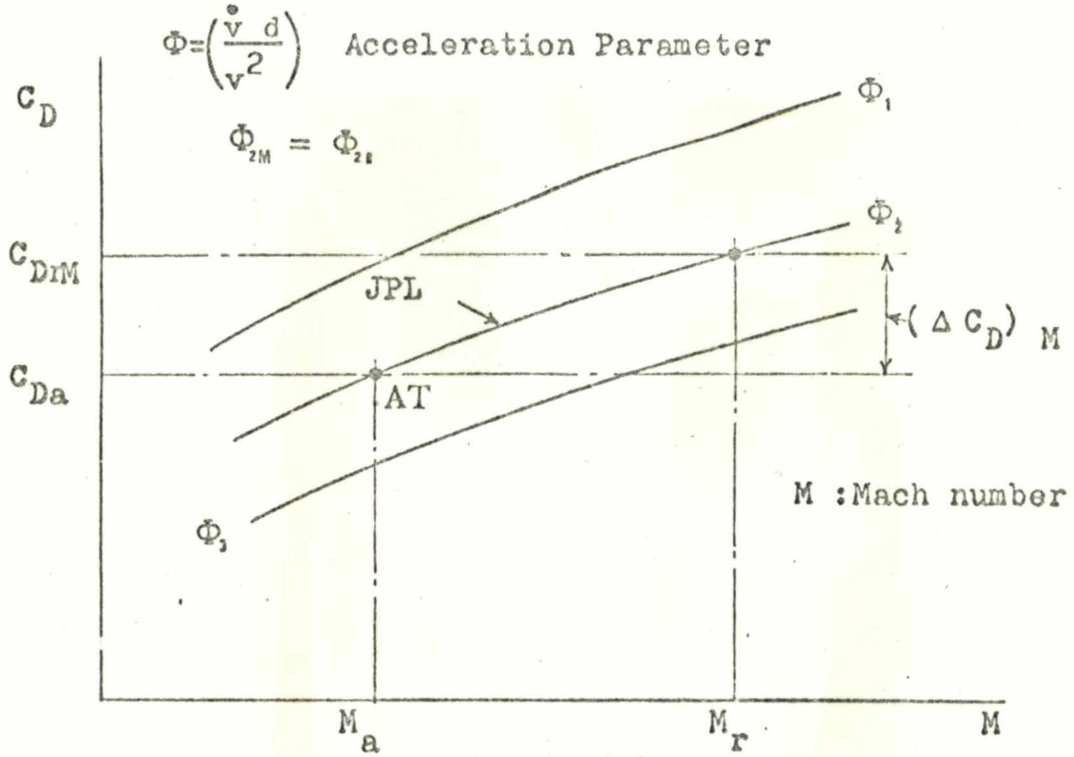

Figure (2)

Mach Number Correction for Unsteady flow

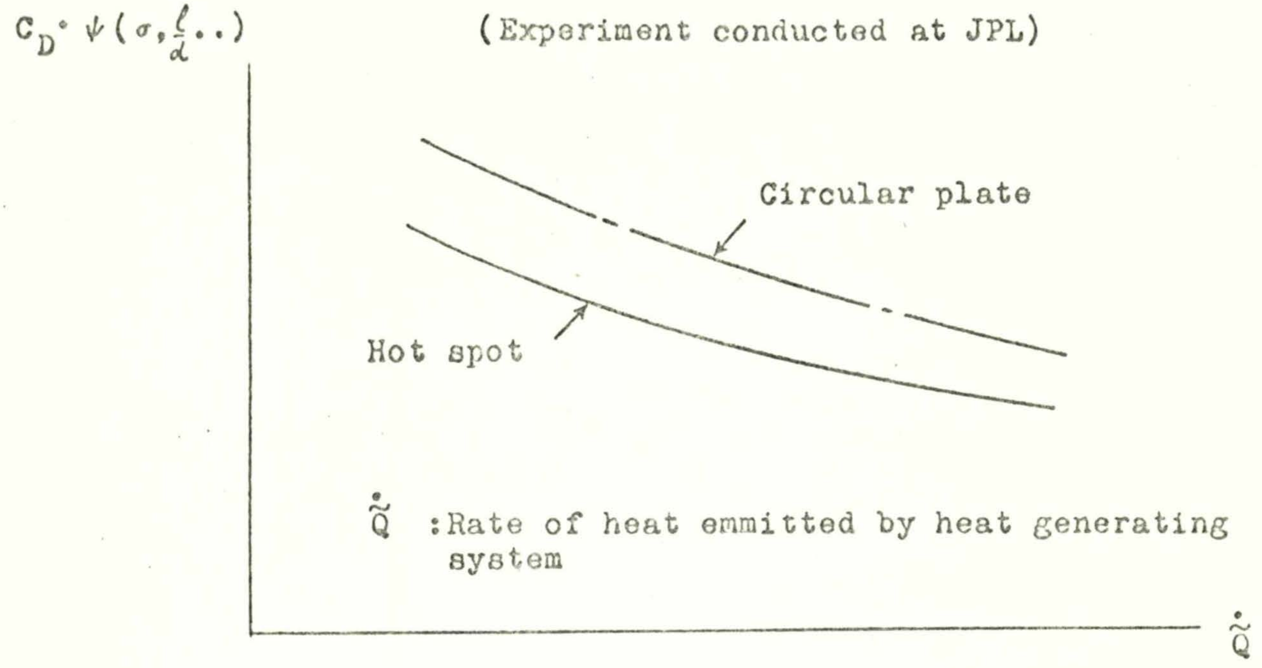

Figure (3)

Experiments for the determination of the effect of geometry of the heat generation system on the Thermodynamic Parameters

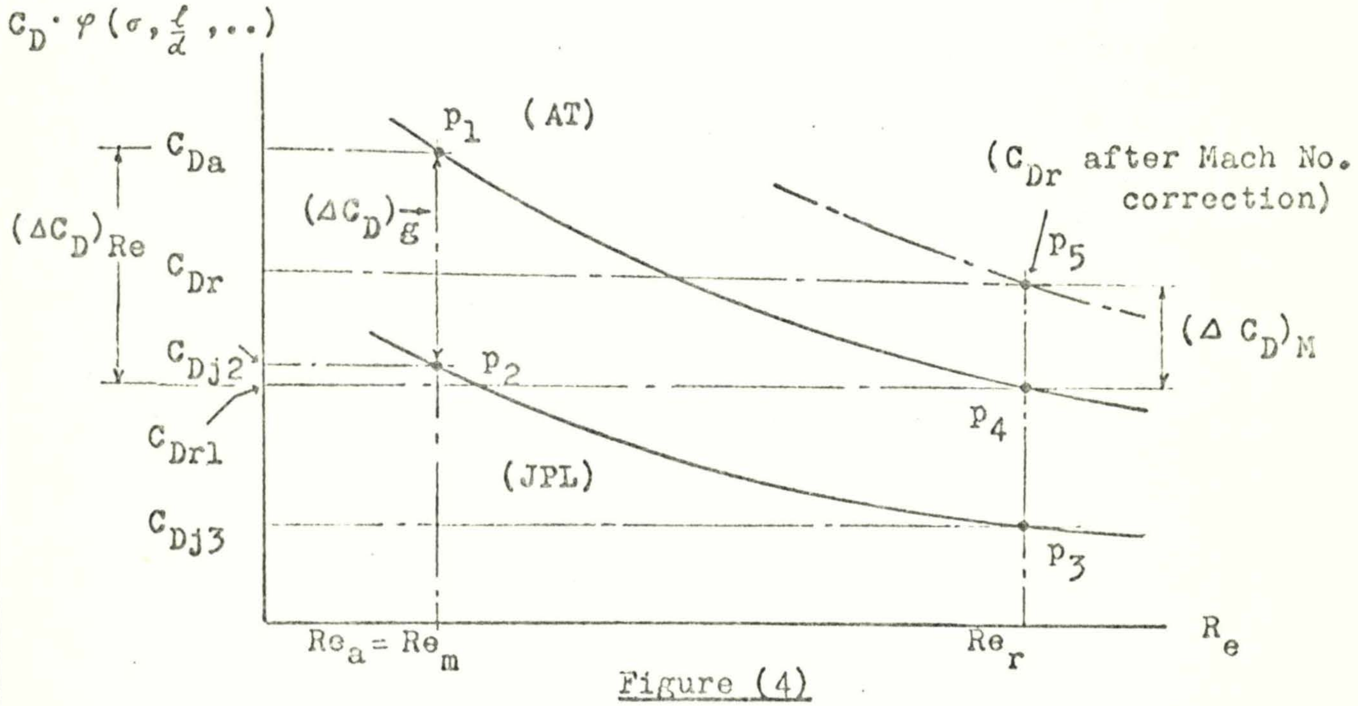

Figure (4)

Geometry, Reynolds Number and Mach Number corrections for unsteady Aerodynamic Flow