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Computer program for calculation of mean value properties for non-uniform compressible flows

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We are constantly striving to develop new work and review data already issued. Any comments arising out of your use of our data, or any suggestions for new topics or information that might lead to improvements, will help us to provide a better service.

THE PREPARATION OF THIS DATA ITEM

The work on this particular Data Item was monitored and guided by the Internal Flow Panel. This Committee first met in 1979 and had the following membership:

Chairman

Dr J.A. Eaton — National University of Ireland, Galway

Members

Mr D.A.Campbell	— Independent
Dr P.R.N.Childs	— University of Sussex
Mr S.C.Curzons	— Rolls-Royce plc
Prof D.H.Freeston *	— University of Auckland, New Zealand
Dr W.R.Geddes	— BNFL Consultancy Services
Mr A.J.Green	— BHR Group Ltd
Dr A.Johnson	— Schlumberger Cambridge Research
Prof J.L.Livesey	— Independent
Dr P.G.Long	— Cambridge University
Dr S.J.Murray	— W.S. Atkins Consultants Ltd
Dr J.T.Turner	— University of Manchester

* Corresponding Member.

The construction and subsequent development of the Data Item was undertaken by

Mr B.C. Freeman — Senior Engineer.

The person with overall responsibility for the work in this subject area was Mr S. Pugh, Head of Thermofluids Group.

The ESDU Fluid Mechanics, Internal Flow Series is recognised as a valuable source of validated data and methods by the Institution of Mechanical Engineers and its Thermofluids Group is involved in continually reassessing the scope and focus of the content of this Series.

COMPUTER PROGRAM FOR THE CALCULATION OF MEAN VALUE PROPERTIES FOR NON-UNIFORM COMPRESSIBLE FLOWS

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COMPUTER PROGRAM FOR THE CALCULATION OF MEAN VALUE PROPERTIES FOR NON-UNIFORM COMPRESSIBLE FLOWS

1. INTRODUCTION

Design and performance analysis methods for ducted flow systems often involve an explicit or implicit assumption that the flow is uniform across a section. In practice, some degree of spatial non-uniformity is present in all real ducted flow systems and, consequently, it is often necessary to formulate a set of representative mean properties to describe a non-uniform flow and to use in the analysis methods.

The use of appropriate mean values is important, for example, in the calculation of component performance when the inlet and outlet profiles are significantly different and in cases where the variation of properties across a profile is large. Mean values are often used to provide a simplified flow description at component interfaces and an appropriate choice is particularly important in ensuring consistency between calculations for separate components of a system, such as a gas turbine engine, that may be analysed independently by different groups.

This Data Item complements a group of Items^{5,7,10} concerned with the definition of mean values and mean-value sets for the one-dimensional representation of steady, spatially non-uniform flows and their use in the analysis of system performance. References 5 and 7 are concerned primarily with definition of the *reference-mean* mean-value-set for compressible flow*. If there are no constraints on the choice of mean values, use of the reference-mean set is recommended. Its principal advantages over historical approaches to flow averaging are that it is thermodynamically-consistent, it retains the correct sectional entropy and therefore allows a true measure of efficiency for processes in which profiles change, it is application-independent, providing a universal definition across component interfaces and it avoids attributing hypothetical losses to the flow upstream or downstream of the measurement station. It requires no more input information than that required for any mass-flow based method.

The Data Item provides information on the use of, and background to, a computer program for calculation of mean-value properties at a section in a duct flow. The methods are applicable to steady, spatially non-uniform (profiled) compressible flows, assumed to be essentially axial, i.e. free from significant crossflows such as radial flow and swirl. The flow property profiles may be derived from experimental measurements, in which case measurement uncertainties on the raw measurements are assumed to be accounted for separately so that the calculation starts with a “corrected” set of measurements. Alternatively, the flow property profiles may be derived from computational fluid dynamics analysis methods or specified as analytical power-law profiles.

Section 2 relates the notation used in output files from the program to notation used in the text of the Data Items. Some specific terminology used to describe gas property calculations is also explained.

Section 3 describes access to the program, which is available as an executable file.

The input data required by the program are described in Section 4. The program requires input of profile information for static pressure, total pressure or axial velocity and total temperature or profile definition by input of power-law parameters. The principal application is to radial profiles in circular or annular ducts and profiles across one direction only of rectangular ducts. However, a more general input option is included that allows for profiles varying in two dimensions and for other duct shapes.

* Reference 9 considers the application of the same methodology to incompressible flows.

Output from the program is described in Section 5. The program calculates local property values across the profile and uses these to derive sectionally-integrated values and mean values. Although use of the *reference-mean-set* is recommended, the program calculates a wide range of mean-value properties from other definitions for comparison with the reference-mean set and for continuity with previously-used methods. The calculated mean values fall into one of several groups as described below.

- Mean property values that form part of thermodynamically self-consistent mean-value-sets, notably the reference-mean values (Appendix A.3).
- Mean-set factors allowing the derivation of sectionally-integrated extensive properties of the profiled flow from the mean property values (Appendix A.3). A minimum number of these factors forms an essential part of any complete mean-value-set.
- Mean values that are part of groups for which, historically, only a few basic mean properties have been used, such as mass-derived mean values. These groups have, where possible, been extended to cover a full set of mean flow properties. Often the original derivations were restricted to isenergetic (uniform total temperature) flows of calorically-perfect gases. Again the methods have been extended to cover the more general case with total-temperature profiles and for thermally-perfect gases where this is feasible (Appendix A.4).
- Miscellaneous mean values that are derived from particular mean-specific extensive properties, such as enthalpy-derived mean values (Appendix A.5).
- Profile factors relating two different mean-value definitions of a particular property. These are useful in indicating the magnitudes of differences between definitions. In this program these profile factors nearly all use the reference-mean-set values as the comparison (Appendices A.3, A.4, A.5).

Two worked examples are described in Section 6, for which input and output files are listed in Appendix D.

Appendix A gives brief descriptions of the mean-value properties calculated. Appendix B lists the unit sets allowed in the program and gives conversion factors and other default parameters included within the program. Appendix C gives a glossary of some terms used in the Item and related terms that may be encountered in the literature.

2. NOTATION AND TERMINOLOGY

2.1 Notation

Data Items	Program output		SI Unit
$A, \delta A$	AREA, dA	cross-sectional area of flow at duct section, element of flow area	m^2
A_{eff}	–	effective cross-sectional area of flow at duct section	m^2
a	a_s	speed of sound in gas	m/s
B_t, b_t	B_t, b_t	sectional availability, specific availability (see Appendix C)	J, J/kg
C_d	C_d	mass-flow mean-set factor or discharge coefficient	–
c_p	c_p	specific heat capacity at constant pressure	J/kg K
c_v	c_v	specific heat capacity at constant volume	J/kg K
D_i	DI	inner diameter of annular duct	m
D_o	DO	diameter of circular duct, outer diameter of annular duct	m
E_{an}, e_{an}	E_an, e_an	sectional anergy, specific anergy (see Appendix C)	J, J/kg
E_{ex}, e_{ex}	E_ex, e_ex	sectional exergy, specific exergy (see Appendix C)	J, J/kg
E_i, e_i	E_i, e_i	sectional internal energy, specific internal energy	J, J/kg
E_k, e_k	E_k, e_k	sectional kinetic energy, specific kinetic energy	J, J/kg
F_a, f_a	F_A, f_a	sectional absolute stream force, dynalpy or impulse function, specific* absolute stream force, dynalpy or impulse function	N, N/kg
F_M, f_M	F_M, f_m	sectional momentum force, specific* momentum force	N, N/kg
H, h	H, h	sectional enthalpy, specific enthalpy (H also used for annulus height, h for distance across annulus from inner wall)	J, J/kg (m)
h_{tr}	HTR	hub to tip radius ratio of annular duct	–
I_E	I_E	kinetic-energy mean-set factor	–
I_{ht}	I_ht	total-enthalpy mean-set factor	–
I_M	I_M	momentum mean-set factor	–
I_p	I_p	static-pressure mean-set factor	–

See footnote at end of table.

Data Items	Program output		SI Unit
I_{pt}	I_pt	total-pressure mean-set factor	—
I_T	I_Ts	static-temperature mean-set factor	—
$I_{\theta t}$	I_phit	total constant-pressure-entropy-function mean-set factor	—
J	J	profile factor relating two definitions of a mean value for a profiled-flow thermodynamic property	—
M	Ma	Mach number	—
m_w	m_w	molecular mass of gas	kg/kg-mol
$\dot{m}, \delta\dot{m}$	MDOT, dmdot	mass flow rate or mass flux through section, mass flow rate through specified area element	kg/s
n	n	exponent parameter in power-law profile definition	—
p	p_s	static pressure	Pa (N/m ²)
p_t	p_t	total pressure	Pa (N/m ²)
pr	pr	isentropic pressure ratio	—
Q_{ss}, Q_{ts}, Q_{tt}	Q_ss, Q_ts, Q_tt	mass flow functions [†]	—
q	—	general symbol for flow property	dependent on property
R	Rg	specific gas constant, $R = R_u/m_w$	J/kg K
R_i	RI	inner radius of annular duct	m
R_o	RO	radius of circular duct, outer radius of annular duct	m
R_u	Ru	universal gas constant, 8314.3 J/kg-mol K	J/kg-mol K
r	r	local radial distance from centre-line of circular duct	m
S, s	S, s	sectional entropy, specific entropy	J/K, J/kg K
T	T_s	static temperature	K
T_e	T_e	environmental or ambient temperature	K
T_t	T_t	total temperature	K
V	V_a	axial velocity	m/s
v	—	specific volume	m ³ /kg
vr	—	isentropic specific volume ratio	—

See footnote at end of table.

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Data Items	Program output		SI Unit
Y	Y	width of rectangular duct in plane of profile	m
y	y	distance across profile from wall	m
Z	Z	width of rectangular duct normal to profile	m
δ	delta	profile-layer thickness (see Appendix B.3)	m
γ	gamma	ratio of specific heat capacities, c_p/c_v	–
θ	theta	constant-volume specific entropy function	J/kg K
ρ	rho_s	static density of gas	kg/m ³
ρ_t	rho_t	total density of gas	kg/m ³
ρ_r	-	isentropic density ratio	–
ϕ	phi	constant-pressure specific entropy function	J/kg K

* For area-weighted mean values, “specific” refers to force per unit area (N/m²) rather than per unit of mass flux as used more generally.

† The symbols Q_1 , Q_2 and Q_3 are often used for these, or closely related, quantities.

Subscripts

Where appropriate, subscripts are used in combination. In the program output files, subscripts are denoted by an underscore separating them from the main notation symbol, multiple subscripts are separated by commas, *e.g.* $T_{S, mw}$.

Data Items	Program output	
A	-	denotes integration over whole duct area at section
a	a	denotes axial component of velocity
aw	aw	denotes area-weighted-mean value (see Appendix A4.1)
e	e	denotes value at environmental or ambient conditions
$edge$	edge	denotes value at free edge of profile layer (see Appendix B.3)
ei	ei	denotes value related to specific internal energy
hs, ht	hs, ht	denote values related to static and total enthalpy
lm	lm	denotes logarithmic-mean value (see Appendix C)
md	md	denotes mass-derived mean value (see Appendix A4.3)

mm	mm	denotes momentum-mixed mean value (see Appendix A3.2)
mw	mw	denotes mass-flow-weighted-mean value (see Appendix A4.2)
$\dot{m}$	-	denotes integration over whole of mass flow at section
p, p_t	p_s, p_t	denote values related to static and total pressures
rms	rms	denotes root-mean-square value
rma	rma	denotes value derived from area-weighted mean kinetic energy
s	s	denotes static-state value
T, T_t	T_s, T_t	denote values related to static and total temperatures
t	t	denotes total-state value
tm	tm	denotes enthalpy-mixed (temperature-mixed) mean value (see Appendix A3.3)
xm	xm	denotes pseudo-mixed mean value (see Appendix A3.4)
θ_s, θ_t	-	denote values related to static and total constant-volume entropy functions
ρ_s, ρ_t	-	denote values related to static and total densities
ϕ_t	$phit$	denotes value related to total constant-pressure entropy function
0	0	denotes value of datum condition or of gas property at that condition

Superscripts

Data Items	Program output	
*	*	denotes value at sonic conditions ($M = 1$)
—	(implied by appropriate 'subscript')	an over-bar denotes mean value of type defined by subscript
~	denoted by 'subscript' tilde	an over-tilde denotes property of the reference-mean flow

2.2 Terminology

For convenience, three operators* are defined to relate gas properties and gas temperature. These are:

- Tcp – constant-pressure specific-heat-capacity operator;
 $c_p = \text{Tcp}\{T\}$ is interpreted as the value of “ c_p is determined at temperature T from an appropriate $c_p \sim T$ relationship for the gas”
- Tsh – specific enthalpy operator;
 $h = \text{Tsh}\{T\}$ is interpreted as “the value of specific enthalpy, h , is determined at the temperature T from an appropriate $h \sim T$ relationship for the gas”.
- Ts ϕ – constant-pressure specific-entropy-function operator;
 $\phi = \text{Ts}\phi\{T\}$ is interpreted as “the value of constant-pressure specific-entropy-function, ϕ , is determined at the temperature T from an appropriate $\phi \sim T$ relationship for the gas”.

The same relationship must be used for the definition of both static-state and total-state values of a particular property, *e.g.* the static- and total-enthalpy definitions, $h_s = \text{Tsh}\{T\}$ and $h_t = \text{Tsh}\{T_t\}$, must both use the same $h \sim T$ relationship.

Further operators may be defined similarly for other gas properties as;

- Tcv – constant-volume specific-heat-capacity operator,
- Tse – specific internal-energy operator,
- Ts θ – constant-volume specific-entropy-function operator,
- Tpr – isentropic pressure ratio operator.

Corresponding inverse operations are defined for each of the operators, using the same property relationships as for the forward operation. For example, the inverse of the operation $h_s = \text{Tsh}\{T\}$ is expressed as $T = \text{Tsh}^{-1}\{h_s\}$, interpreted as “the value of static temperature, T , is obtained from the value of specific static enthalpy, h_s , by inverse use of an appropriate $h \sim T$ relationship”. This relationship must be the same as is used in the forward direction.

These operators are implemented in the program through relationships in the form of equations or tabulated data.

Appendix C gives a glossary of other terms that are used in this Item or may be encountered in related literature.

* The “T” in these operators derives from the historical use of the terminology “true c_p calculations” in connection with the use of a varying c_p vs T relationship in contrast to a constant (and by implication imprecise) c_p value.

3. THE COMPUTER PROGRAM

The computer program is supplied as a ready-to-run executable program, A0312Vxx.EXE (where Vxx denotes the version).

3.1 Access to the Program

3.1.1 Subscribers to Internal Flow Series in Hard Copy (Paper) Format

The executable program is supplied on CD-ROM. Installation instructions are supplied. The default installation is to a directory/folder C:\ESDUpacs\A0312. Example input and output files are provided. A dll file Salflibc.dll is required to run the executable and is also installed in this directory.

3.1.2 Subscribers to Internal Flow Series on CD-ROM

The executable program is installed as part of the Series installation. The default installation is to a directory/folder C:\ESDUpacs\A0312. Example input and output files are provided. A dll file Salflibc.dll is required to run the executable program and is also installed in this directory.

3.1.3 Subscribers to Internal Flow Series via the World Wide Web (Internet)

Both versions of the program can be downloaded from the ESDU Web Site (www.esdu.com). The program can be located under Programs on the abstract page associated with ESDU 03012 (select Internal Flow Series ... Volume 1 ... Item 03012).

3.2 Running the Program

The program requires one or more prewritten input files containing the necessary input data. Section 4 describes the data required and provides a tabulated guide to construction of the input files. The input file must be separately assembled using a file editor that can save the file as an unformatted ASCII script.

Output from the program is to a formatted file, named by the user, summarising the input data and listing calculated results as requested by the user. A second output file, named CHK0312, is also written which includes a full set of calculated results. This file is overwritten by any subsequent program run but can be copied to provide a permanent record.

3.2.1 Executable program

The computer program is supplied as program A0312Vxx.EXE (where Vxx denotes the version number).

The executable program can be run in a Command Prompt Window from a command line of the form

```
A0312Vxx < inputfile
```

where `inputfile` is the name of the input data file to be used and `xx` is replaced by the appropriate version number. This assumes that both files are in the directory from which the program is run, otherwise the required paths should be inserted before the file names. The output file name is read from the input file and should not be specified on the command line. Unless a path is supplied with the output file name, the output file will be written to the directory from which the program is run.

The program cannot be run by double-clicking the executable file name or from the Windows "Run" command on the "Start menu".

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4. PROGRAM INPUT DATA

The program requires one or more prewritten input files containing the necessary input data. The input files must be assembled following the guidance in the tables in this section, using a file editor that can save the file as an unformatted ASCII script.

The input data required by the program is divided into four groups of related entries: general data, duct cross-section data, flow conditions data and gas property data. Each group of entries is described in more detail in subsequent sections which guide the user through the setting up of appropriate input files.

Each entry in the input file must be preceded by the appropriate *entry label* in quotes *e.g.* the first entry under general data input might be 'G01', 'INPUT FILE 1'. The program uses this label to assign the input to the appropriate input variables. Where the Tables indicate "No entry required", the corresponding entry label should be omitted also. If more than one entry is required, these may be entered on one line (up to 256 characters in length) or may be spread over several lines. The entry label should appear only at the start of the first line of that block of input data otherwise data previously entered will be overwritten.

Comments, which are ignored as far as program input is concerned, may be included in the input file by commencing a line with the letter C. Blank lines are also ignored.

Apart from the secondary file name, any of the input in any category may be provided in a secondary input file. This is particularly convenient in the case of gas property data, allowing the gas property data to be set up once and used with a variety of other input data. It is preferable to provide a complete path from the root of the drive to ensure that the file is found.

The order of entries within the files is not critical except where a line continues a block of entries but the listed order will allow easier checking of input files.

4.1 General Data (Table 4.1)

This Section provides identification of the input file and the user-named output file into which the calculated results will be written and a title for the particular run.

Selection of SI units or one of a number of sets of British units is available for input data and separately for output data which can be in a different set of units. The units of gas property data are selected separately by an entry in Section 4.4. The unit sets, and associated conversion factors, are specified in Appendix B.

A choice of the data output to the user-named output file is set by entry G08, a full set is always written to CHK0312 but is overwritten by subsequent runs. For a fuller description of the output options, see Section 5.

4.2 Duct Cross Section and Dimensions Data (Table 4.2)

Entry 'S01' defines the cross section shape and entry 'S02' defines how the geometry will be specified.

For annular or rectangular sections, the geometry can be specified in non-dimensional terms, with the values scaled to a specified area or to unit area by appropriate input.

If the flow property profile data (Section 4.3) are entered in terms of sets of values associated with specified areas or proportions of total area, details of the cross section shape are not used by the program. They can be entered for record purposes if required or the non-specific Section Type 6 can be used.

If the profiles to be described vary in two dimensions, cross-section type 6 should be used together with flow conditions input as values for specified area elements (Entry P01 = 1, Table 4.3a).

4.3 Flow Conditions Data (Tables 4.3a, 4.3b and 4.3c)

Apart from the file name entry labelled 'P99', any of the flow conditions input data can be entered in a separate input file if required.

Input is required to define the variation of flow properties across the duct and how this is interpreted in the calculation. The environmental or ambient conditions can also be specified in this input section.

The program uses the input flow profile data to generate a "calculation array" consisting of a set of specified elements of duct flow area over each of which the flow properties are approximated as having constant values.

Two groups of input flow properties can be input to the program:

- | | |
|---------|--------------------------------------|
| group 1 | values of p_s , p_t and T_t or |
| group 2 | values of p_s , V_a and T_t . |

For either group, the input flow properties can be defined in one of three formats.

- Format 1 Input of a table of specified elements of duct area with associated local flow property values applicable over each area element. Input entries for this format are detailed in Table 4.3a.

The elemental area can be specified as a proportion of the total duct area (in which case the duct geometry input (Table 4.2) must include at least the total duct area) or as an absolute elemental area (in which case the duct geometry input is used only to check the summation of area elements and is not essential). Duct geometry specification Type 6 is compatible with this input format.

The calculation array is identical to the input array for this format.

- Format 2 Input of flow property profiles specified by location across the duct and value. Input entries for this format are detailed in Table 4.3b. The three property profiles may be defined in a single table or in three separate tables which need not be of the same size.

The profiles are assumed radial or two-dimensional, for three-dimensional profiles use input Format 1. The location can be specified as either the ratio of distance across duct to duct width or as an absolute distance from the centreline for a circular duct or from the inner wall for an annular duct.

The duct geometry (Table 4.2) is required to define the calculation array locations. Duct geometry specification Type 6 is not compatible with this flow-conditions input format. The calculation array is generated from the input data by interpolation of the input profiles. If the calculation array reference locations differ from the input data reference locations in any profile, the program calculates values by cubic spline interpolation of the input profiles. A natural spline is used by default.

Output option 1 can be specified to review the interpolated profiles.

Input of 0 for Entry P08 will prevent interpolation provided that all profiles are specified at the same locations (uniform profiles can still be specified by just one or two values). However, the relationship of the area elements to the input locations must still be specified in order to generate the calculation array.

Format 3 Input of analytical power-law definitions of the flow property profiles. Input entries for this format are detailed in Table 4.3c.

The two forms of profiles included in the program are described in Appendix B. The profiles are assumed to be radial or two-dimensional but the two profile layers for annular or rectangular ducts need not be the same.

The duct geometry (Table 4.2) is required to define the locations. Duct geometry specification Type 6 is not compatible with this input Format.

The calculation array is generated from the input data by calculation from the power-law specifications.

Output option 1 can be specified to review the calculated profiles.

For input formats 2 and 3, the required geometry of the calculation array must be specified. The area elements can be defined as of equal area or based on equally-spaced radial locations or user-specified radial locations (entry P08). The position of the reference location within the element can be defined to be at either the mid-radius or the mid-area of the element (entry P09).

4.3.1 Sampling interval

The effect of sampling interval for the input property profiles depends on both the shape and the amplitude of the profiles. From extensive studies of power-law profiles, it was found that, in some cases, calculated mean values required as many as 200 evenly distributed points across the profiles to reach a constant value whereas in others as few as 10 was adequate. In practice, a real profile may be sampled at only a few points and it is desirable that the distribution of measurements be such that regions of rapid property change are defined at the most frequent intervals.

The program provides an option to interpolate the input profiles at more frequent intervals using a cubic-spline interpolation (using a natural spline by default). The results of such interpolation should be treated with caution as there is often limited detail in measured profiles in regions of rapid property change. The results of the interpolation can be seen by including output Option 1 in the output required (entry G08, Table 4.1). The user should check that the interpolated profiles are acceptable and, if not, the available profiles should be interpolated by an alternative method to give a more extensive set of data for input.

4.3.2 Mass-flow compensation

A measured value of mass flow rate is sometimes available from a source independent of the local flow property measurements across a profiled flow. In such circumstances, it is usually the case that the integrated sectional mass flow rate derived from the local flow properties does not match exactly the measured mass flow rate. It is common practice then to adjust one or more of the locally-measured profiles so that matching is achieved.

This feature is not available in Version 1.0 of the program but will be added to later versions.

4.4 Gas Property Data and Reference Constants (Tables 4.4a, 4.4b, 4.5a, 4.5b)

Apart from the file name entry labelled 'D99', any of the gas property input data can be entered in a separate input file if required. This allows equation or tabulated data specific to a particular gas used to be kept in a separate data file and called as required. If a separate file is used, it is recommended that it should contain all of the required entries in the range D02 to D34.

The gas can be specified as calorically-perfect (constant c_p) or as thermally-perfect ($c_p = f\{T\}$).

For a calorically-perfect gas, the specific heat capacity, c_p , can be specified directly or can be calculated at a specified temperature from a set of reference data for the gas.

For a thermally-perfect gas, the gas properties are calculated from a set of reference data for the gas.

Two options, polynomial curve fits and data tabulation, are provided for specification of gas properties for a thermally-perfect gas or for use in the calculation option for a calorically-perfect gas.

Default data providing a good representation of air properties are invoked by entering 0 for entry D03 in the case of direct input for a calorically-perfect gas or by entering 0 for entry D15 if a gas properties are to be calculated for either a thermally-perfect or a calorically-perfect gas. The default values used are described in Appendix B2.1.

4.4.1 Units for gas properties

The units of the reference gas property data are specified in this section (entry 'D02') and can differ from those of the main body of input to allow for use of historical databases and formulations. Any default constants used will be converted as appropriate.

4.4.2 Equations for gas properties

The form of the equations is based on a polynomial fit to data for c_p for the gas. Thus for c_p ,

$$c_p = c_1 + c_2 T + c_3 T^2 + c_4 T^3 + c_5 T^4 + \dots \quad (4.1)$$

If only c_p coefficients are specified, it is assumed that the enthalpy can be obtained by integration as $\int c_p dT$, to give,

$$h = h_D + c_1 T + \frac{c_2}{2} T^2 + \frac{c_3}{3} T^3 + \frac{c_4}{4} T^4 + \frac{c_5}{5} T^5 + \dots, \quad (4.2)$$

where h_D is a constant* to allow matching of data at the joins of ranges of applicability.

Similarly, the constant-pressure entropy function can be obtained by integration as $\int \frac{c_p}{T} dT$ to give

$$\phi = \phi_D + c_1 \ln T + c_2 T + \frac{c_3}{2} T^2 + \frac{c_4}{3} T^3 + \frac{c_5}{4} T^4 + \dots, \quad (4.3)$$

where ϕ_D is a constant to allow matching of data at the joins of ranges of applicability.

* Note that h_D and ϕ_D are purely computational constants and not necessarily datum values.

Up to three equations for each property can be specified. If the constants h_D and ϕ_D are entered as 0, the program will calculate appropriate values with the assumption that the value at the upper end of each successive lower-temperature range is correct.

Alternatively, coefficients for polynomial equations for each of c_p , h and ϕ can be entered separately, in which case equations of the forms of Equations (4.1) to (4.3) are used. The constant-pressure specific heat capacity c_p is then given by

$$c_p = c_{p1} + c_{p2}T + c_{p3}T^2 + c_{p4}T^3 + c_{p5}T^4 + \dots, \quad (4.4)$$

the specific enthalpy, h , by

$$h = c_{h1} + c_{h2}T + c_{h3}T^2 + c_{h4}T^3 + c_{h5}T^4 + c_{h6}T^5 + \dots \quad (4.5)$$

and the constant-pressure entropy function, ϕ , by

$$\phi = c_{\phi1} + c_{\phi2} \ln T + c_{\phi3}T + c_{\phi4}T^2 + c_{\phi5}T^3 + c_{\phi6}T^4 + \dots \quad (4.6)$$

Note the retention of a term in $\ln T$ in Equation (4.6), this coefficient should be set to zero if this term is not required.

Coefficients and constants for up to three ranges of applicability can be entered (*i.e.* 3 values of c_{p1} , c_{p2} , c_{h1} , *etc.*) for each property. Each equation can include up to 10 coefficients. The same number of coefficients must be entered for each equation for a particular property, with any not actually required entered as zero, to ensure correct allocation within the program. The program may extrapolate beyond the lower and upper temperature limits in evaluating inverse relationships but will warn if any final calculated value is outside those limits.

4.4.3 Tabulated data for gas properties

For constant c_p , a single value only of c_p is necessary but this can be interpolated from a more extensive data set if necessary. For variable c_p , tabulation of all of c_p , h and ϕ is necessary. The program uses a natural cubic spline interpolation to interpolate the data sets.

The data may be entered as a single table of T , c_p , h and ϕ or as three separate tables of T and c_p , T and h and T and ϕ .

The program may extrapolate beyond the lower and upper temperature limits in evaluating inverse relationships but will warn if any final calculated value is outside those limits.

4.4.4 Sources of data for gas properties

A default set of equation coefficients is included within the program, derived from data in Reference 2 (as quoted in Reference 4) and providing a good representation of properties for air. These data are also supplied as a separate gas data reference file, A0312DT1.SRC. Reference 4 also quotes equations for c_p (from Reference 2), for a variety of other gases.

A tabulated data set is supplied with the program, with data calculated from the default equations, in a separate gas data reference file A0312DT2.SRC.

If difficulties are encountered when using the separate data files, check that the file location is correctly specified, including the path.

Tabulated data for air and other gases can also be found in References 1, 3 and 6. Reference 8 provides comprehensive equations from which properties may be computed.

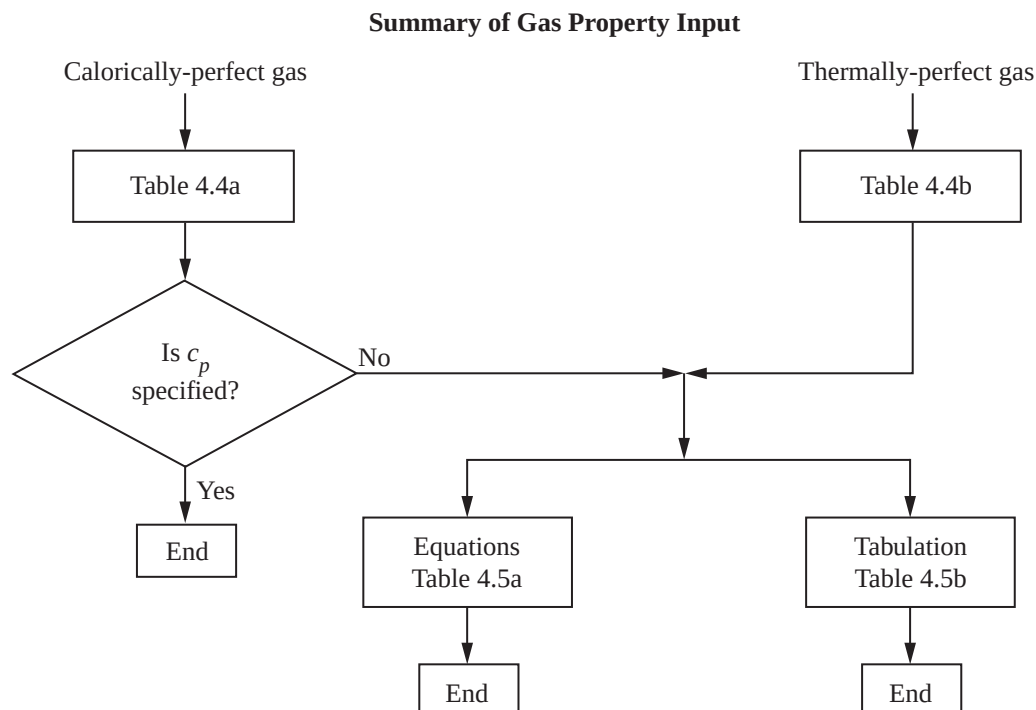
4.4.5 Gas property and environmental reference data

The program requires a value for the gas constant for the gas. This can be entered directly or can be calculated from the universal gas constant by specifying a value for the molecular mass of the gas.

Datum values for gas properties are required, particularly for calculations assuming a calorically-perfect gas and also for calculation of derived properties for a thermally-perfect gas. These are the temperatures at which the specific enthalpy (and specific internal energy) and constant-pressure specific entropy function (and constant-volume specific entropy function) are taken as zero and the pressure at which the specific entropy is taken as zero at the datum temperature.

For some calculations, *e.g.* calculation of availability, the ambient or environmental conditions must be specified, these are entered under the flow conditions input (Tables 4.3a, 4.3b, 4.3c) if required.

Default values for these reference data are available within the program as specified in Appendix B2.2. The default datum temperatures and pressure have been chosen such that they make no numerical contribution to the property values. These defaults can be invoked explicitly or by omission of the relevant input entries, they are also substituted for invalid input.



Sketch 4.1 Summary of Gas Property Input

TABLE 4.1 Input of General Data

Entry label	Program data entry	SI Unit	Program Variable
'G01'	Enter file name for input file (up to 256 characters, including appropriate path* if required) between quotes. This name is not used by the program but is echoed to the output file to record the source of the input data.	–	INPFIL
'G02'	Enter file name for output file (up to 256 characters, including appropriate path* if required) between quotes. If an invalid name is entered or the entry is omitted, a default name of RSA0312 will be substituted.	–	OUTFIL
'G03'	Enter data set name or run title. Up to 10 lines if required, each of up to 75 characters between quotes. Each line must start with the entry label. These entries may be omitted if not required.	–	TITLE(n)
Entries 'G05' and 'G06' are not used by this program.			
'G06'	Specify units [†] set for output data: set 1 for SI units, other options are listed in Appendix B.1. This unit set may differ from the input set chosen below.	–	UNITSO
'G07'	Specify units [†] set for input data; set 1 for SI units, other options are listed in Appendix B.1. This unit set may differ from the output set chosen above.	–	UNITSI
'G08'	Output required: enter 0 to output options 1 to 11, 1 to output basic local[‡] properties; δA, $\delta \dot{m}$, p, p_t, T, T_t and V_a. 2 to output additional local properties; c_p, γ, M_a, ρ_s, h_t, ϕ_t, s and b_t, 3 to output sectionally-integrated properties, 4 to output reference-mean properties and mean-set factors, 5 to output momentum-mixed mean properties and mean-set & profile factors, 6 to output enthalpy-mixed mean properties and mean-set & profile factors, 7 to output pseudo-mixed mean values and mean-set & profile factors, 8 to output area-weighted mean properties and profile factors, 9 to output mass-flow-weighted mean properties and profile factors, 10 to output mass-derived mean properties and profile factors, 11 to output miscellaneous mean properties and profile factors, 12 to output a summary of mean temperatures, pressures, enthalpies and entropies, 13 to output a summary of temperature, pressure, enthalpy and entropy profile factors, 14 to output all calculated local properties. Enter numbers for the required output options in a continuous sequence separated by commas or spaces, e.g. 1,4,3,9. Numbers need not be in order; 0 anywhere in the sequence will output options 1 to 11 inclusive, options 12 to 14 can be added explicitly. The output options are specified in more detail in Section 5.	–	TYPOUT
General data input is complete, continue with duct geometry data.			

* The input and output files will usually be located in the directory from which the program is run. If a path is specified it is assumed to be a path relative to the current directory unless an absolute path from the root directory is specified.

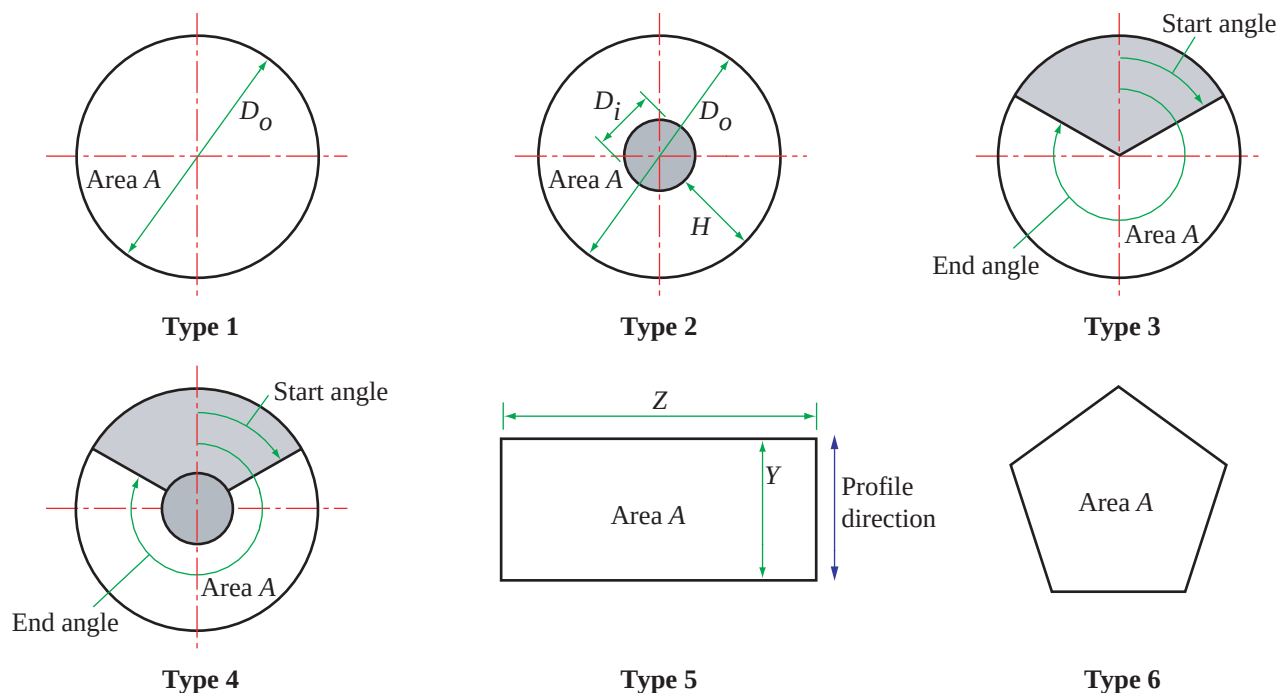
[†] Units for the gas-property reference data are specified in Table 4.4a or 4.4b and may differ from input or output data units.

[‡] For power-law profiles this will include boundary and profile-layer edge values to aid plotting of profiles.

TABLE 4.2 Input of Duct Cross Section and Dimensions

Entry label	Program data entry	SI Unit	Program variable
'S01'	Enter 1 to specify a circular section, 2 to specify an annular section, 3 to specify a circular sector, 4 to specify an annular sector, 5 to specify a rectangular section, 6 to specify a non-specific section*.	–	TYP SN(1)
'S02'	Enter 1 to input duct area (and hub/tip ratio or aspect ratio if required) or enter 2 to input duct diameter(s) or side lengths.	–	TYP SN(2)
'S03'	If entry S01 is 1 or 3; if entry S02 is 1, enter area of cross section, A , or if entry S02 is 2, enter diameter of cross section, D_o .	m^2 or m	$A1$ or $DO1$
	If entry S01 is 2 or 4; if entry S02 is 1 enter annulus area, A , and hub/tip ratio, D_i/D_o , or if entry S02 is 2 enter inner and outer diameters of annulus, D_i & D_o .	m^2 , - or m, m	$A1, HTR1$ or $DI1, DO1$
	If entry S01 is 5; if entry S02 is 1, enter duct area, A , and aspect ratio defined as (dimension across profile, Y) / (dimension normal to profile, Z) or if entry S02 is 2, enter duct side lengths Y and Z .	m^2 , - or m, m	$A1, YBYZ1$ or $SY1, SZ1$
	If entry S01 is 6; enter area of cross section, A .	m^2	$A1$
'S04'	If entry S01 is 1, 2, 5 or 6, no entry required.	–	–
	If entry S01 is 3 or 4, enter angular extent of sector defined by angle at start and angle at end.	degree, degree	$INSR2(1), INSR2(2)$
Duct geometry data input is complete, continue with flow conditions data.			

If Type 6 is selected, the flow conditions data can be entered only in terms of values associated with specified area elements (Table 4.3a).

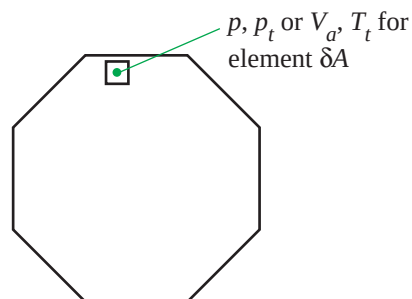


Sketch 4.2 Definition of Duct Geometry

TABLE 4.3a Input of Flow Conditions as Property Values for Local Area Elements

Entry label	Program data entry	SI Unit	Program variable
'P99'	If any flow conditions data are entered in a separate input file, enter the file name (up to 256 characters, including appropriate path* if required) between quotes. <u>This entry must be in the main input file.</u>	–	FLOFIL
'P00'	If a separate input file is provided, enter headings for this file (up to five lines, each up to 75 characters between quotes). This entry may be omitted if not required.	–	FLOHD(n)
'P01'	Enter 1 for input of local flow properties and associated elements of area.	–	TYPPR(1)
'P02'	Enter 1 to input p_s , p_t and T_t ; enter 2 to input p_s , V_a and T_t .	–	TYPPR(2)
Entry 'P03' is not used in this version of the program.			
'P04'	Enter the ambient (environmental) temperature and pressure. If this entry is omitted, default values will be used (see Appendix B2.2).	K,Pa	TAMB,PAMB
'P05'	Enter 1 if the area element will be specified as a proportion of total flow area ($\delta A / A$) (this is the default if this entry is omitted); enter 2 if the area element will be specified as an absolute area (δA).	– m ²	TYPPR(5)
'P06'	Enter number (up to 200) of sets of values to be input.	–	NVALS
'P07'	If entry P02 is 1; enter NVALS sets of [$\delta A / A$ or δA , p_s , p_t and T_t] for each element of area.	–, Pa, Pa,K	DAR(n),PS(n), PT(n),TT(n)
	If entry P02 is 2; enter NVALS sets of [$\delta A / A$ or δA , p_s , V_a and T_t] for each element of area.	–,Pa, m/s,K	DAR(n),PS(n), VA(n),TT(n)
Flow conditions input for Entry P01 = 1 is complete, continue with gas property data.			

* The input files will usually be located in the directory from which the program is run. If a path is specified it is assumed to be a path relative to the current directory unless an absolute path from the root directory is specified.



Sketch 4.3 Flow Conditions Input for Format 1