DIMENSIONAL ANALYSIS AND PERFORMANCE LAWS FOR ORGANIC VAPOR FLOW TURBOMACHINERY

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ABSTRACT

Dimensional analysis is performed for compressible flow covering non-perfect gas dynamics to define appropriate similarity numbers for organic vapor flows and corresponding turbomachinery performance. The Buckingham-Rayleigh theorem states that the compressibility factor Z is not a primary similarity number for organic vapor flows. At least one new similarity number is required for organic vapor flows in addition to the conventional perfect gas similarity numbers. As a limit case of the new dimensional analysis, the well-known similarity numbers for a perfect gas result, and then the isentropic exponent-similarity follows. The theoretical analysis is applied to flow applications utilizing the closed-loop organic vapor wind tunnel test facility CLOWT at Muenster University of Applied Sciences. These applications cover the experimental investigation of the flow of an organic vapor past a circular cylinder and a centrifugal organic vapor compressor's performance. The outcome of the considered test cases supports the main findings of the dimensional analysis.

1 INTRODUCTION

The most thorough comprehension of turbomachines' general behavior is obtained from dimensional analysis (Dixon and Hall, 2010). Dimensional analysis is a procedure whereby the set of variables characterizing the physics is reduced to smaller dimensionless groups (or similarity numbers). Virtually every textbook (e.g., Granger 1995) covers its application to incompressible and compressible perfect gas flows. Still, relatively little is known regarding dimensional analysis and performance laws for organic vapor flows. Wong and Krumdieck (2016) discussed gas turbines' scaling from air to refrigerants for organic Rankine cycle applications using a similarity concept directly based on the well-known expressions for perfect gas turbomachinery. Their results show that the approach cannot achieve complete similarity for the same turbomachinery with two different working fluids. Recently, Giuffre and Pini (2020) proposed design guidelines for axial turbines operating with compressible non-perfect gas flows after revising the classical similarity equation. In this context, they mentioned a new dimensionless number referred to as molecular complexity. Still, Giuffre and Pini rewrote the classical similarity equation utilizing the volumetric flow ratio and the exponent for the general isentropic pressure-volume relation.

Following the classical similarity equation might be of considerable practical interest for establishing design guidelines for axial turbines. Still, it is hard to understand specific aspects of non-perfect gas dynamics. For instance, in the compressible perfect gas flow, a similarity exists regarding the isentropic exponent γ (also called γ-similarity). The compressibility factor Z is already dimensionless like γ, but nothing is known regarding its impact on similarity or performance laws. Furthermore, it is reasonable to assume that at least one additional quantity is necessary to cover the molecular complexity in organic vapor flows. However, there should be a connection between perfect and non-perfect gas flows in the sense that similarity or performance laws obtained for a non-perfect flow should naturally reduce to the well-known classical laws in the limit case of a perfect gas.

A general compressible flow dimensional analysis is performed in the following. The study considers two configurations: compressible flow past objects (without the need to introduce the running speed n) and the classical performance laws for turbomachinery (with running speed n).

2 DIMENSIONAL ANALYSIS

It is essential to recognize that the outcome of dimensional analysis is not a strict physical law. The predictions of dimensional analysis are only as good as choosing the relevant control variables or input parameters. Consequently, all appropriate physical quantities have to be identified, leading to a substantial number of parameters. On the other hand, similarity or performance laws are only useful for practical purposes if the number of independent similarity numbers or dimensionless groups of variables is not too large. That issue requires that only the dominant physical mechanisms and corresponding variables are to be selected.

2.1 Buckingham-Rayleigh Method

The Buckingham-Rayleigh method starts with the selection of the relevant physical parameters x_i, including their dimensions. In the following, the dimensions length (L), time (T), force (F), and temperature (Θ) are chosen. Then, see Granger (1995), it is stated that the desired quantity X can be expressed as a power law of the relevant physical parameters with suitable exponents m_i:

$$X = C \ \prod_i x_i^{m_i} \tag{1}$$

Based on this fundamental assumption and the fact that physics does not depend on our specific system of dimensions, it is possible to formulate simple algebraic equations for the exponents m_i yielding finally suitable dimensionless groups π_j of variables. Thus every similarity number, say, for instance, π_1, can be expressed functionally by the following relation

$$\pi_1 = f(\pi_2, \pi_3, \dots) \tag{2}$$

Buckingham's π-theorem states that the largest numbers of non-dimensional groups or dimensionless numbers are equal to the number of physical variables minus the number of primary dimensions (in the majority of situations, see Granger (1995)).

2.2 Compressible Flow past an Object

As a first case, the compressible flow past an object is analyzed in the framework of dimensional analysis. To be concrete, the drag F created by a circular cylinder with diameter D subjected to a compressible uniform stream is assumed in the following (section 3 presents results of an experimental study concerning this specific configuration).

In any case, the following input parameters are relevant flow quantities x_i: length scale L, time scale or inflow velocity v, inertia or density ρ, and dynamic viscosity μ. The thermodynamic quantities are usually evaluated at (total) inlet conditions. In addition to the primary flow variables, the thermodynamic state has to be quantified for compressible flow. For doing this, the (total inflow) temperature T_{01} is specified as a physical parameter (in addition to the density ρ_{01}). Other thermodynamic parameters like pressure p might be selected in principle, but here it is convenient to choose the temperature. The bulk modulus

$$K = -\mathrm{v} \left(\frac{\partial p}{\partial \mathrm{v}}\right)_s \tag{3}$$

represents compressibility effects for any fluid (gases, vapors, liquids, and even solids). Finally, the molecular complexity has to be expressed through a suitable variable. Since the specific gas constant R is always defined for a gas using its molecular mass M, this quantity serves as an input parameter. In the most basic form of dimensional analysis, there is no need to introduce a more complex parameter like the molecular complexity defined by M, R, and the isochoric specific heat at the critical point suggested by Harinck et al. (2009).

Inserting the selected physical variables into equation (1), solving the algebraic equations for the exponents m_i which arises from the dimensional analysis, and collecting in respect to dimensions yield, after some calculations which are described in detail by Granger (1995)

$$\frac{F}{\frac{1}{2}\rho_{o1}\, v^2} = f\left(\frac{vD\rho}{\mu}, \frac{v}{\sqrt{K/\rho}}, \frac{RT_{o1}}{v^2}\right) \tag{4}$$

The first dimensionless group in equation (4) is the Reynolds number Re = $vD\rho/\mu$. The second group is the Mach number Ma = $v/a = v/(K/\rho)^{1/2}$. In the limit case of a perfect gas obeying the thermal equation of state $p\text{v} = RT$ and the isentropic relation $p\text{v}^{\gamma}$ = constant, the following identities hold:

$$\gamma\left(\frac{\partial p}{\partial \rho}\right)_T = \left(\frac{\partial p}{\partial \rho}\right)_s, \; a = \sqrt{\left(\frac{\partial p}{\partial \rho}\right)_s} = \sqrt{\gamma RT} \tag{5}$$

and then the Mach number reduces to the well-known ideal gas expression Ma = $v/(\gamma RT)^{1/2}$. The third dimensionless group, $\mathrm{Ec}^{*-1} = RT/v^2$, might be interpreted as an Eckert number expression. Usually, the Eckert number is defined by Ec = $v^2/(c_pT)$. To distinguish the current definition from the usual one, the symbol * is introduced. In the case of a perfect gas, the identity Ec = $(\gamma - 1)\mathrm{Ma}^2$ holds. In this case, the Eckert number similarity can be replaced by a so-called γ-similarity as frequently done in steam and gas turbine design (Deijc and Tojanovskij (1973)). The Eckert number should be interpreted as a representation of dissipation effects and not of compressibility effects; see Gersten and Herwig (1992) for a further discussion.

In Table 1, the general similarity numbers and their limit expressions for the perfect gas are listed for a compressible flow. There is no direct impact of the compressibility factor Z on the similarity numbers or performance laws. The bulk modulus K and the specific gas constant R represent the specific gas behavior. The value of the bulk modulus K depends in general on temperature T and density ρ for a fluid. The Reynolds number Re and the Mach number Ma = v/a with a as the sound speed are always significant similarity numbers. A third similarity number is given by the Eckert number Ec*. This similarity number can be replaced by a so-called γ-similarity in the case of a perfect gas. In the case of compressible organic vapor flows at a higher Mach number level, that γ-similarity is only approximately satisfied. For small Mach number flows, Ma → 0, only the Re-similarity has to be considered since the other groups tend to zero. Finally, it is remarked that the relative roughness, k_s/L, with k_s as equivalent sand grain roughness, would join the parameter set for hydraulically rough objects.

Table 1: Similarity numbers for the compressible flow past an object

	π_1	π_2	π_3
General gas flow	Re = $vD\rho/\mu$	Ma = $v/(K/\rho)^{1/2}$	Ec* = $v^2/(RT_{o1})$
Perfect gas flow	Re = $vD\rho/\mu$	Ma = $v/(\gamma RT)^{1/2}$	Ec = $v^2/(c_pT_{o1})$ or γ-similarity

2.3 Scaling Laws for Organic Vapor Turbomachinery

Dimensional analysis for compressible flow turbomachines differs from the flow past a passive object as discussed in subsection 2.2 on account of the following factors: The inflow velocity v is replaced by the running speed n for covering the characteristic time scale, the mass flow rate $\dot{m}$ and the total inlet pressure p_{o1} are additional relevant performance parameters. Performing a similar dimensional analysis as before, one gets for the total pressure ratio p_{o2}/p_{o1} or efficiency η the functional relationship

$$\frac{p_{o2}}{p_{o1}}\;, \; \eta = f\left(\frac{n\,D^2\rho}{\mu}, \frac{n\,D}{\sqrt{K/\rho}}, \frac{n\,D}{\sqrt{RT_{o1}}}, \frac{\dot{m}}{\varrho_{o1}\,n\,D^3}\right) \tag{6}$$

A similar relationship can also be formulated for the power coefficient, but since this quantity is not considered in more detail in the following experimental study, it is omitted here. The selection of the total pressure ratio requires some remarks. From an experimental or practical point of view, the use of total pressures is attractive since these quantities can be measured relatively easily. From a more general perspective, the use of stagnation enthalpy changes might be more appropriate. In the case of a perfect gas, both approaches are equivalent, but some deviations might be expected for real gas applications. Then, the main challenge is that temperature changes affect the entire process. However, the following treatment focuses more on practical and experimental aspects, and hence the total pressure ratio is still chosen in equation (6).

The first dimensionless group on the right-hand side of equation (6) is the Reynolds number, Re = $nD^2\rho/\mu$. If the machine operates only at high Reynolds numbers, Re can be dropped in performance analysis (Dixon and Hall (2010)). The second dimensionless group can be referred to as Mach number Ma = $nD/(K/\rho)^{1/2} = nD/a_{o1}$ (all material properties have to be evaluated at total inlet state). The third group, $nD/(RT_{o1})^{1/2}$, is a modified Eckert number expression, although it looks like a Mach number. It is also possible to interpret this group as a dimensionless running speed $n^+ \sim n/\sqrt{T_{o1}}$. In the limit case of a perfect gas, the second and the third dimensionless group can be replaced by the Mach number Ma = $nD/(\gamma RT)^{1/2}$ and the γ-similarity. This set might be more convenient for practical applications. The last group may be referred to as flow capacity or dimensionless mass flow rate. It is possible to rewrite this similarity number using the other dimensionless groups and the fact that the quantity p_{o2} is directly related to the group $p_{o1}/(D^2n^2\rho)$. Instead of equation (6), it is hence possible to express the functional relationship as

$$\frac{p_{o2}}{p_{o1}}\ ,\ \eta = f\left(\frac{n\,D^2\rho}{\mu}, \frac{n\,D}{\sqrt{K/\rho}}, \frac{n\,D}{\sqrt{RT_{o1}}}, \frac{\dot{m}\sqrt{RT_{o1}}}{p_{o1}\,D^2}\right) \tag{7}$$

In the latter form, the similarity to the well-known ideal gas expression becomes more apparent. However, there is still a formal difference: In the general case, the specific gas constant R is used, whereas the isobaric specific heat c_p is frequently used in the perfect gas case (Dixon and Hall (2010)). That replacement of the material parameters is possible due to the γ-similarity for a perfect gas. In Table 2, the general similarity numbers and their limit expressions for the perfect gas are listed for compressible fluid turbomachinery performance laws. Once again, there is no direct impact of the compressibility factor Z on the similarity numbers or performance laws. The relative roughness, k_s/L, with k_s as equivalent sand grain roughness, would join the parameter sets for hydraulically rough blades of turbomachinery. In the case of substantial heat transfer phenomena within the turbomachinery, the Prandtl number would be of relevance, too.

It has become customary for machines of known size and fixed working fluid to delete D, γ, R, and c_p from the dimensionless groups in perfect gas applications. Furthermore, the Reynolds number is frequently dropped if the machine operates at sufficiently high levels of Re. Then, only two quasi-similarity variables, namely $n^+ \sim n/\sqrt{T_{o1}}$ and $\dot{m}^+ \sim \dot{m}\sqrt{T_{o1}}/p_{o1}$, describe the performance of such turbomachinery. Neglecting the Reynolds number effect, these two quasi-similarity variables are essential in non-perfect gas case. However, the bulk modulus expression K_{o1}/ρ_{o1} depends in general on the thermodynamic state and does not reduce to an expression proportional to $\cdot T_{o1}$ for a non-perfect gas. Hence, the performance of organic vapor turbomachinery is in general only approximately described by the two quasi-similarity variables $n^+ \sim n/\sqrt{T_{o1}}$ and $\dot{m}^+ \sim \dot{m}\sqrt{T_{o1}}/p_{o1}$. For a rigorous comparison of a machine of known size and given working fluid, the Mach number level Ma has to be considered as an additional similarity number joining the primary parameter set.

Table 2: Similarity numbers for compressible fluid turbomachinery performance laws

	π_1	π_2	π_3	π_4
General flow	Re = $nD^2\rho/\mu$	Ma = nD/a_{o1} = $nD/(K_{o1}/\rho_{o1})^{1/2}$	Ec*$^{1/2}$ = n^+ = $nD/(RT_{o1})^{1/2}$	$\dot{m}^+ = \frac{\dot{m}\sqrt{RT_{o1}}}{p_{o1}\,D^2}$
Perfect gas flow	Re = $nD^2\rho/\mu$	Ma = nD/a_{o1} = $nD/(\gamma RT_{o1})^{1/2}$	γ-similarity	$\dot{m}^+ = \frac{\dot{m}\sqrt{c_pT_{o1}}}{p_{o1}\,D^2}$

3 EXPERIMENTAL TESTS

Only experimental tests can judge how well the obtained dimensionless similarity numbers represent the actual physical problem. Two tests of the predictions of the dimensional analysis of section 2 were conducted, namely the determination of the drag coefficient of a circular cylinder and the performance of a centrifugal compressor.

3.1 Test Facility and Working Fluid

The experimental tests were performed using the test facility CLOWT at Muenster University of Applied Sciences. CLOWT stands for a closed-loop organic vapor wind tunnel, and it is described in more detail in previous publications (e.g., Reinker et al. (2018, 2019)). Figure 1 illustrates the test facility and its main components. The electrical heating system and the thermal insulation are not shown in Figure 1 for better orientation.
After passing the centrifugal compressor with adjustable running speed n, the organic vapor is decelerated in the diffuser. It enters the settling chamber, equipped with a chiller to achieve stable steady-state operation. In the settling chamber, total temperature and total pressure are measured, corresponding to exit conditions of the compressor, including the diffuser. After a first contraction (low-speed nozzle), the fluid enters the high-speed test section. In the test section pipe, a high-speed nozzle (second contraction) and a test object can be placed, if desired. The circulating working fluid mass flow rate $\dot{m}$ is recorded utilizing a mass flow device in the subsonic return of the closed-loop wind tunnel where also pressure and temperature values are recorded as compressor inlet conditions. Various compressor operation points can also be controlled by a throttle valve. Due to the charging of the wind tunnel, different density levels can be investigated. The present experiments were performed with the perfluorinated ketone Novec™ 649 as working fluid for the test facility CLOWT. Besides, some experiments with dry air were conducted, too. In Table 3, some thermophysical properties for air and Novec 649 at two different pressure levels are listed.

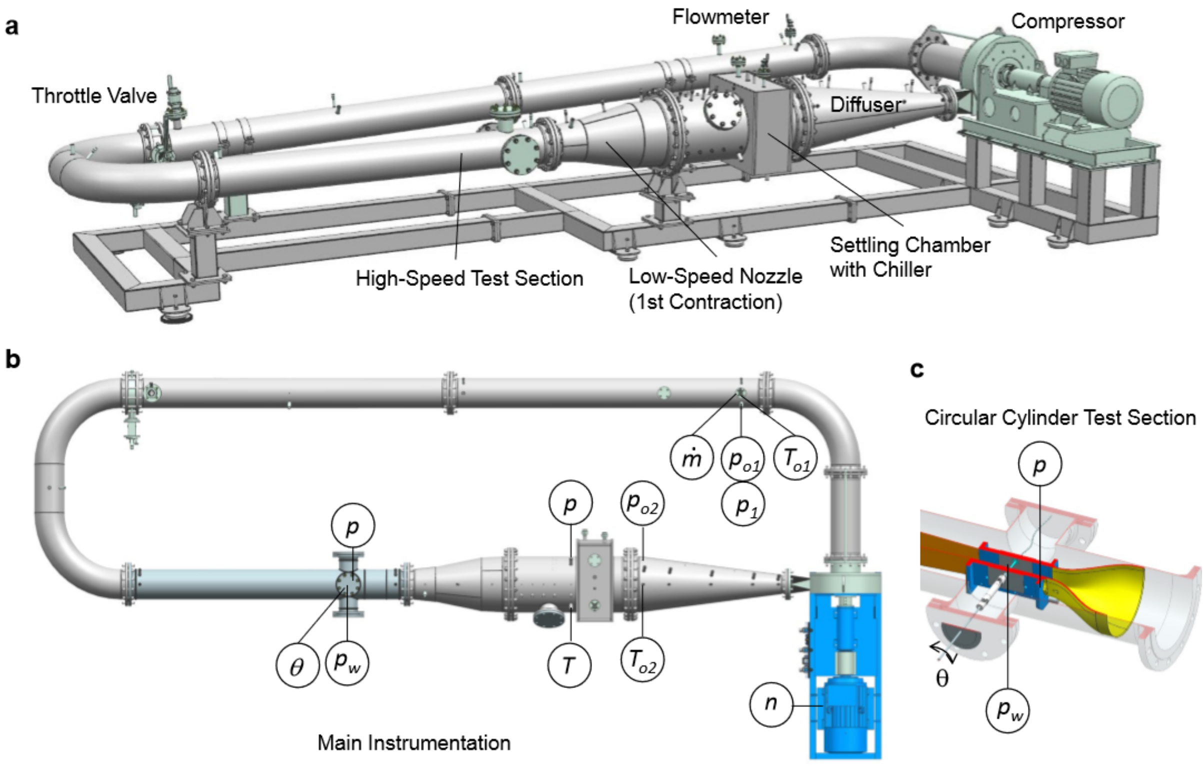

Figure 1: Closed-loop organic vapor wind tunnel CLOWT: **a** main components **b** instrumentation **c** detail view on circular cylinder test section placed in the high-speed test section

Table 3: Thermophysical properties of Novec 649 and dry air (calculated by REFPROP 9.0)

	R [J/(kg K)]	Z [-]	$\gamma = c_p/c_v$ [-]	a [m/s]
Air at 1.0 bar and 20°C	287.10	1.00	1.400	343
Novec 649 at 1.5 bar and 97°C	26.31	0.95	1.04	95
Novec 649 at 3.1 bar and 97°C	26.31	0.88	1.06	88

Due to its complex molecules, the specific gas constant R of Novec 649 is much smaller than that for air. In the considered pressure and temperature range, the isentropic exponent γ and the speed of sound a of Novec 649 were much smaller, too. With increasing pressure levels, the compressibility factor of Novec 649 becomes smaller. Its value deviates noticeably from the ideal gas value $Z = 1$.

3.2 Flow Past a Circular Cylinder

As a first test case, the drag coefficient of a circular cylinder subjected to a uniform stream of air and Novec 649 were analyzed concerning the dimensionless groups listed in Table 1. Figure 1.c provides a look into the details of the circular cylinder test section. The new Novec 649 experiments were conducted with a circular cylinder with a diameter $D = 5$ mm in the high-speed test section of CLOWT. Details about the experiments can be found elsewhere (Reinker et al. (2020, 2021)). The cylinder was equipped with a small pressure hole (0.5 mm) for measuring the cylinder wall pressure p_w (equal to p_0 at the stagnation point at circumferential angle $\theta = 0°$). The entire circumferential pressure distribution $p_w(\theta)$ was obtained by rotating the cylinder through a rotatable sealed shaft and an angle meter. After integration of $p_w(\theta)$, the form drag coefficient C_D was obtained and compared with literature results available for air at identical Mach and Reynolds numbers.

From literature (Macha (1976), Ackerman et al. (2008)) it is known that compressibility effects become noticeably for Ma > 0.4 and that the drag coefficient C_D does not substantially depend on the Reynolds number Re at a sufficiently high Reynolds number level (i.e., Re > 10^5). The drag coefficient's high sensitivity has been observed in the transonic regime (Ma about unity). Hence, the Mach number range of 0.6 < Ma < 0.7 was assumed to be suitable for assessing the present dimensional analysis predictions. The outcome of this comparison is shown in Figure 2. The new Novec 649 data points fitted well into the scattered literature results obtained at air (Novec and air data's deviations were smaller than the maximum scattering of literature data). A direct effect of the compressibility factor Z was not observed. The reasonable agreement can be explained by the fact that not only the Mach and Reynolds numbers were virtually identical in Figure 2, but also the modified Eckert numbers were of the same order of magnitude (Ec* = 0.47 and 0.63 for air, Ec* = 0.29 and 0.35 for Novec 649).

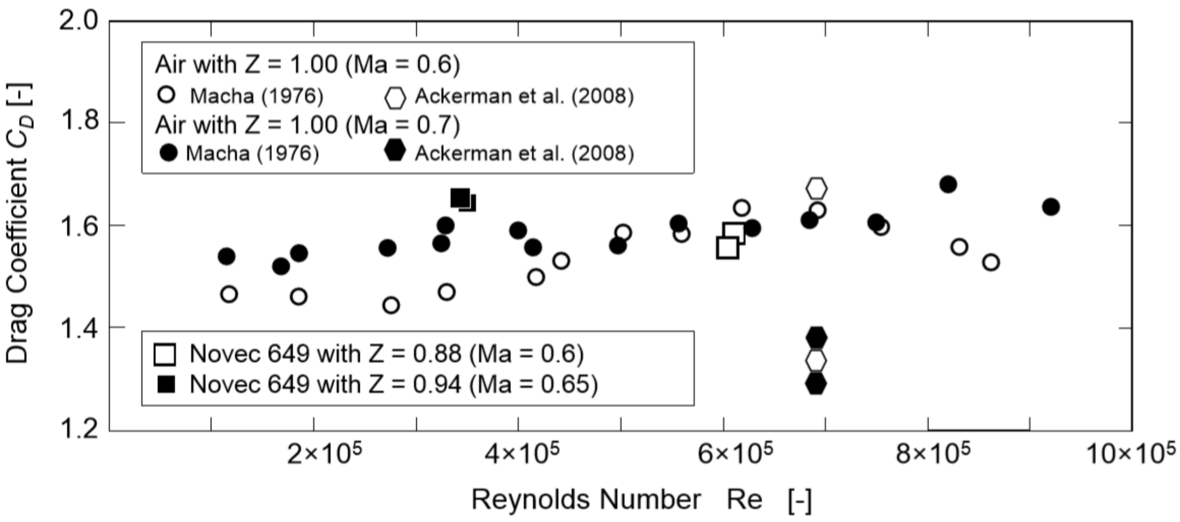

Figure 2: Drag coefficient of a circular cylinder subjected to streams of air and Novec 649

3.3 Performance of a Centrifugal Compressor Operated with Novec 649

Performance data was recorded of the centrifugal compressor installed at the test facility CLOWT during several experiments. A wide range of operation points was achieved utilizing the throttle valve and various running speeds n as shown in Figure 3.

The flowmeter position at the end of the return represented the compressor inlet station where total inlet temperature T_{o1}, static pressure p_1, mass flow rate $\dot{m}$, and total pressure p_{o1} were measured. The pressure drop due to the 90°-bow and the compensator close to the compressor's eye was of only minor importance. The end of the diffuser (i.e., the settling chamber) represented the compressor exit station where the total exit pressure p_{o2} and temperature T_{o2} were recorded. The exact position of the surge line in the compressor map was not determined during the present experiments due to the limited number of operation points. However, an additional probe in the test section indicated an unstable flow or surging in the case of relatively low flow rates.

Figure 3 shows the experimentally determined compressor performance map. The Reynolds number level was high ($Re > 10^6$) for all data points. Two different sets of density ρ_{o1} and compressibility factor Z were investigated for Novec 649. In addition to the various Novec 649 measurements, some low-speed data for air is shown in Figure 3, too. The usual dimensionless groups (flow capacity and dimensionless running speed) cover the compressor performance in Figure 3. Due to different pressure and density levels, the set of dimensionless speeds were not exactly identical for experiments with $Z = 0.95$ and $Z = 0.89$. Remarkably, no direct effect of the compressibility factor Z was observed. Although the Novec 649 data points shown in Figure 3 were obtained for two different values, namely $Z = 0.95$ and $Z = 0.89$, that caused no systematic effect on compressor performance. The compressor performance shown in Figure 3 depended only on the dimensionless running speed and flow capacity as in the case of a perfect gas.

Since Schultz (1962), it is usual in compressor design to consider the compressibility factor Z as an input variable even in perfect gas applications. The present dimensional analysis and the new data indicate that the effect of Z is only indirect: Z might be used for expressing mass flow rates (as done, for instance, by Albusaidi and Pilidis (2015)), but it is not a primary similarity number itself for a perfect gas or an organic vapor in the dilute regime.

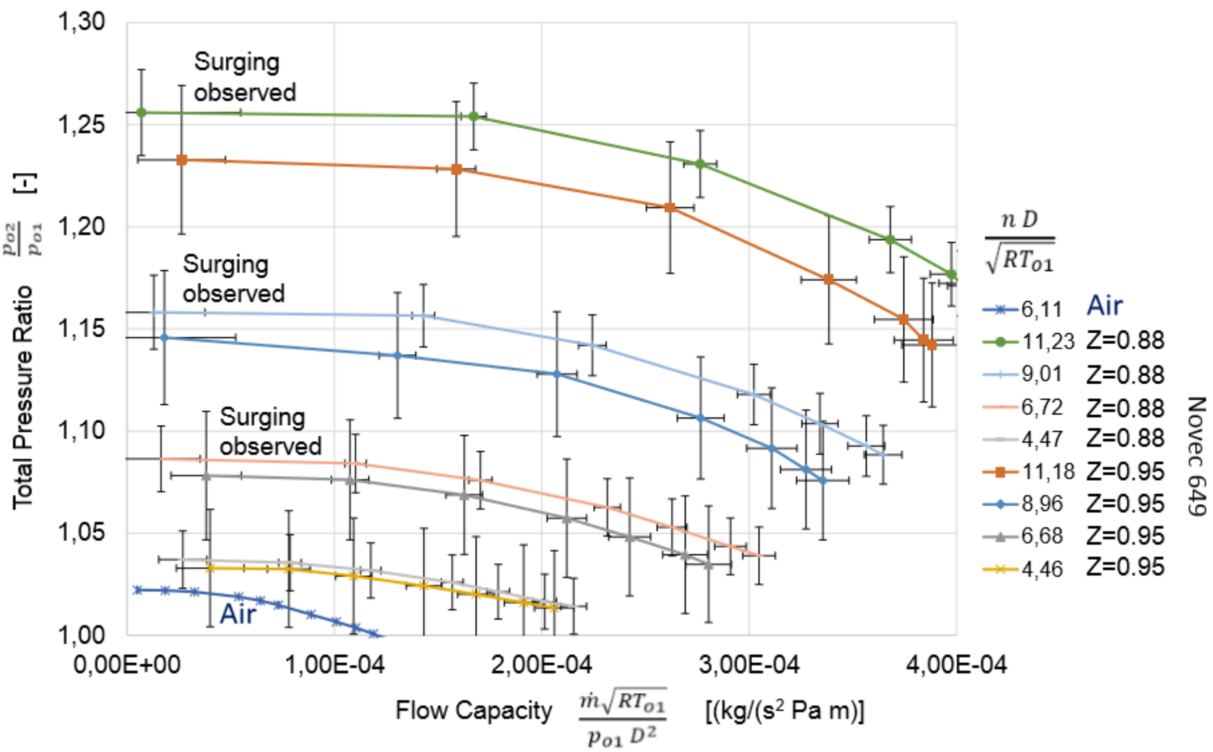

Figure 3: Centrifugal compressor map for Novec 649 (data points with maximum error bars)

4 CONCLUSIONS

This work dealt with a dimensional analysis for compressible flow covering non-perfect gas dynamics. It was found that the compressibility factor Z is not a primary similarity number for organic vapor flows and turbomachinery performance. At least one new similarity number (modified Eckert number Ec*) has to be used for organic vapors in addition to the conventional perfect gas similarity numbers. In the limit case of a perfect gas, the well-known similarity numbers, including the isentropic exponent-similarity result.

Finally, we remark that the present experimental study was conducted with an organic vapor in the dilute gas regime. The modified Eckert number Ec* was of the same level as for studies dealing with air. Thus, the present experimental data and the organic vapor compressor performance were well covered by the primary similarity numbers used in perfect gas flows. Significant deviations might occur if the modified Eckert number Ec* deviates substantially from values typically found in air experiments (e.g., in the dense gas regime of an organic vapor).

NOMENCLATURE

a	speed of sound	m/s	m_i	exponent for variable x_i	-
C	constant	-	Ma	Mach number	-
C_D	drag coefficient	-	n	running speed	1/s
c_p	isobaric specific heat	J/(kg K)	p	pressure	Pa
D	diameter	m	R	specific gas constant	J/(kg K)
Ec	Eckert number	-	R_{un}	universal gas constant	J/(mol K)
F	drag	N	Re	Reynolds number	-
f	functional relationship	-	s	entropy	J/(kg K)
K	bulk modulus	Pa	T	temperature	K
k_s	sand grain roughness	m	v	specific volume	m^3/kg
L	length	m	v	velocity	m/s
M	molecular mass	kg/mol	X, x_i	physical variable	tbd
$\dot{m}$	mass flow rate	kg/s	Z	compressibility factor	-

Greek Symbols

γ	isentropic exponent ($\gamma = c_p/c_v$)	-	π_j	j-th dimensionless group	-
μ	dynamic viscosity	Pa s	ρ	density	kg/m^3
η	efficiency	-	θ	circumferential angle	°

Subscripts

o	total or stagnation state	1	inlet
w	wall (cylinder surface)	2	exit

Superscript

*	modified (Eckert number)	+	dimensionless (n and $\dot{m}$)

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ACKNOWLEDGEMENT

The support by Leander Hake and Robert Wagner during some of the experiments is appreciated.