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Performance Simulation To Understand The Effects Of Multi-Fluid Scaling Of Gas Turbine Components For Generation IV Nuclear Power Plants

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ABSTRACT

A significant hurdle in the development of performance simulation tools to analyse and evaluate nuclear power plants (NPP) is finding data relating to component performance maps. As a result, Engineers often rely on an estimation approach using various scaling techniques. The purpose of this study is to determine the component characteristics of a closed-cycle gas turbine NPP using existing component maps with corresponding design data. The design data is applied for different working fluids using a multi-fluid scaling approach to adapt data from one component map into another. The multi-fluid scaling technique described herein was developed as an in-house computer simulation tool. This approach makes it easy to theoretically scale existing maps using similar or different working fluids without carrying out a full experimental test or repeating the whole design and development process. The results of selected case studies show a reasonable agreement with available data. The analyses intend to aid the development of cycles for Generation IV NPPs specifically Gas-cooled Fast Reactors (GFRs) and Very High-Temperature Reactors (VHTRs).

NOMENCLATURE

Notations

A	flow annulus area m^2
C_p	specific heat capacity, J/kgK
M	Mach number
N	rotational speed, rpm
P	pressure, Pa
P_s	static pressure, Pa
P_t	total pressure, Pa
PR	pressure ratio
PR_c	compressor pressure ratio
PR_t	turbine pressure ratio
R	specific gas constant, J/kgK
T	temperature, K
T_s	static temperature, K
T_t	total temperature, K
V	velocity m/s
W	mass flow kg/s

Greek Symbols

η_c	compressor isentropic efficiency
η_t	turbine isentropic efficiency
θ	referred temperature parameter
δ	referred pressure parameter
γ	ratio of specific heats (Gamma)
ρ	density kg/m^3

Subscripts

c	compressor
cs	case study
DP	design point
OD	off design point
Map	reference map
NG	nozzle guide vane
s	static
t	turbine
1-7	station number
x	axial frame of reference

Abbreviation

CMF	corrected mass flow
CMSF	corrected mass flow scaling factor
COT	core outlet temperature, K
CSSF	corrected speed scaling factor
CS	corrected speed
CW	compressor work, J/kg
GFR	gas cooled fast reactors
ISA	international standard atmosphere

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ISO	international organization for standardization
NGV	nozzle guide vane
NPP	nuclear power plant
$\eta_c SF$	compressor isentropic efficiency scaling factor
$\eta_t SF$	turbine isentropic efficiency scaling factor
PRSF	pressure ratio scaling factor
SF	scaling factor
TW	turbine work, J/kg
VHTR	very high-temperature reactors

INTRODUCTION

In the last two decades, there has been growing efforts in exploring different coolants/working fluids for the Nuclear Power Plant (NPP), especially in the closed-cycle gas turbine systems. The different working fluids which include; the monoatomic inert gases, carbon dioxide, nitrogen, dry air and mixtures thereof, usually work at different conditions and will affect the component design as well as the operating state of the system. Hence, the foremost consideration in the successful development and deployment of this technology is performance simulations.

Performance simulation is necessary to minimise the risks and costs associated with tests to analyse and evaluate power plant designs and operations. With Generation IV (Gen IV) nuclear power plants still under development [1], it is crucial that any simulation of NPP performance is as accurate as possible. This often requires the component data in the form characteristics map to be available [2–4].

In most cases, the data is based on component level testing. However, this information is proprietary and not available. This provides an opportunity to implement different methods to theoretically adapt data from a known component map characterisations, for adaptation into a new map. This is only possible through the analyses and comparison of the modelled design points and available operating data from similar components such as compressors, turbines, heat exchanger and reactors [5,6].

Extensive research work has been conducted to enable the development of methods and techniques [7] to utilise existing component in the creation of new maps. These methods include scaling, statistics and high fidelity mathematical concepts like genetic algorithm, neural networks[8], fuzzy logic and numerical optimization [7,9–12]. However, some numerical methods are not as robust in regenerating data in some off-design operating regions. [12,13].

Therefore, it is important to further demonstrate a thermodynamic approach that could enable one to develop a preliminary component map for different working fluids from an existing reference map. This study describes a multi-fluid scaling approach for adapting component characteristics in closed closed-cycle gas turbine plants. The characteristics are retrieved from known maps and are adapted in new maps, which utilise different coolants or working fluids. Each component operation is defined by an appropriate change of state equations that describes the thermodynamic properties. As such, consideration of the properties of the working fluids is necessary in order to successfully scale the map, thereby ensuring a satisfactory degree of modelling and simulation accuracy.

For scaling purposes, the varying of properties of the working fluid, (such as gamma γ – the ratio of specific heat capacities, C_p- specific heat capacity at constant pressure, R – gas constant) do not provide all the necessary effects in terms of characterisation, without the consideration of the physical component. As variation in Mach numbers and velocity triangles as expected, the combination effects impact the fluid flow area as it travels through the component. For this study, the scaling technique employed assumes that the parameters adopted in component maps are based on Mach number similarity [12,14,15] and inlet area geometry. This allows for different conditions to be derived on the map for various inlet conditions in terms of pressure, temperature and working fluid composition. This holds true for the turbo-components with relatively low-pressure ratios, as required in most closed-cycle gas turbine operations. This essential concept of theoretical scaling allows one to modify an existing map with similar or different working fluids without carrying out a full experimental test or repeating the whole design and development process.

The multi-fluid scaling technique described in this paper was developed using an in-house simulation tool called [2], which can be beneficial for analysing the performance of closed-cycle nuclear gas turbine operations, which use different working fluids.

DESCRIPTION OF REFERENCE MAP AND CASE STUDY ENGINE

The reference component map was adapted from a map library of known engines that have undergone experimental testing and are numerically presented in a high fidelity in-house tool [16]. This tool programme has various component maps that represent different technology levels, with some utilising air as the working fluid. The design point values of the selected map are given in Table 1. The selected map which is described as reference or baseline map belongs to a single shaft gas turbine engine. For this study, the focus is on the turbomachinery components that are responsible for compressing and expanding the working fluid.

The Generation IV (Gen-IV) reactors applicable to this study are the Gas-cooled Fast Reactors (GFRs) and Very High-Temperature Reactors (VHTRs). Typically, both reactors are helium cooled at high temperature, with core outlet temperatures (COTs) between 750℃ (1023K) and 950℃ (1223K). The GFRs uses a fast-spectrum core, while the VHTRs is a thermal plant that utilises a graphite moderator in the solid state. Fig. 1, illustrates a Gen-IV nuclear power plant (NPP) with a primary helium circuit, which is combined with a recuperated closed-cycle engine configuration. For 3 scaling cases, the secondary circuit employs helium (He), nitrogen

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(N_2), and carbon dioxide (CO_2) as working fluids in the map. Table 2 summarises the working fluids properties used in the study. The NPP, which is the focus of this study includes a single turbomachinery set (turbine-compressor), a recuperator at the compressor downstream, a pre-cooler and the nuclear reactor. The performance characteristics at the design point were obtained from the in-house tool, which was developed by the authors [2]. The basic equations for calculating the design point details are as shown in Eqs. (1) – (4).

$$T_3 = T_2 + \frac{T_2}{\eta_c}\left[\left(\frac{P_3}{P_2}\right)^{\left(\frac{\gamma-1}{\gamma}\right)} - 1\right] \quad \textbf{(1)}$$

Where, T_3 is the compressor exit temperature and compressor work can be obtained from [3,17]

$$CW = WC_P(T_3 - T_2) \quad \textbf{(2)}$$

Similarly, the turbine exit temperature is given by:

$$T_7 = T_6 - T_6\eta_t\left[1 - \left(\frac{P_7}{P_6}\right)^{\left(\frac{\gamma-1}{\gamma}\right)}\right] \quad \textbf{(3)}$$

And turbine work is expressed as:

$$TW = WC_P(T_6 - T_7) \quad \textbf{(4)}$$

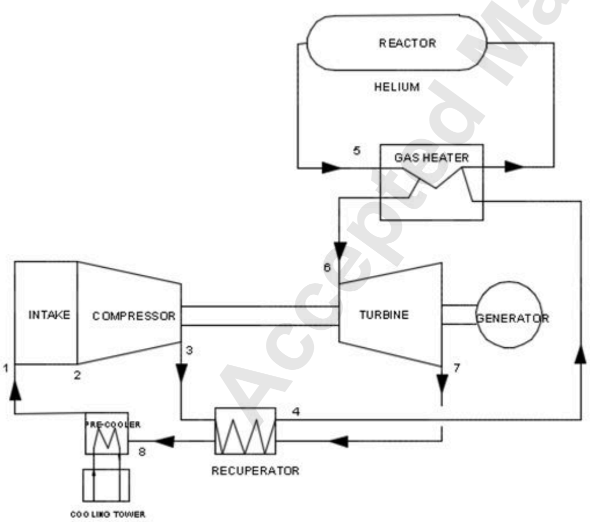

Fig. 1 Schematic representation of the Gen-IV reactor indirectly coupled with a recuperated closed-cycle gas turbine

Table 1: Reference map design point characteristics

Components	Component Details	Reference map
Compressor	Pressure ratio	2.07
	Actual mass flow kg/s	176
	Corrected mass flow kg/s	79.68
	Isentropic efficiency	0.83
	Actual speed rpm	3600
	Working fluid	air
Turbine	Pressure ratio	2.00
	Actual mass flow kg/s	176
	Corrected mass flow kg/s	77.84
	Isentropic efficiency	0.88

Table 2: Working fluid properties

Working fluid	Properties	
Air	Specific Gas Constant R J/kg.K	287
	Gamma (γ)	1.40
Helium	Specific Gas Constant R J/kg.K	2076
	Gamma (γ)	1.66
Carbon dioxide	Specific Gas Constant R J/kg.K	188.9
	Gamma (γ)	1.293
Nitrogen	Specific Gas Constant R J/kg.K	296.7
	Gamma (γ)	1.391

METHOD OF ANALYSIS

The turbomachinery maps are mathematically described using dimensionless parameters. This includes corrected mass flow, corrected speed, pressure ratio, component efficiencies and work functions. These dimensionless parameters are plotted on graphs with polynomial lines of pressure ratio as a function of corrected mass flow for the different corrected speed lines and contour lines of constant efficiency. It is essential when expressing these parameters that the properties of the working fluids are taken into considerations. Hence, the plots consider the properties of the working fluid in question during the thermodynamic calculations.

To demonstrate the multi-fluid scaling technique, an existing map was adapted to new components for a recuperated nuclear power plant described in the previous section. The method used to develop the compressor and turbine maps is indicated in Fig. 2.

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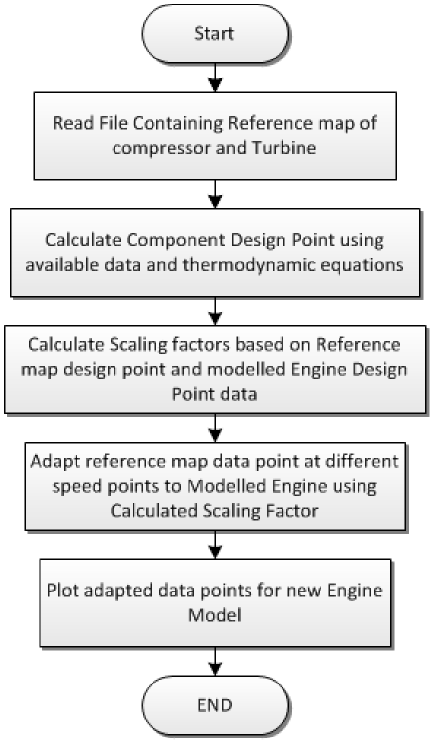

Fig. 2 Flow Chart of Scaling Method for Component Maps

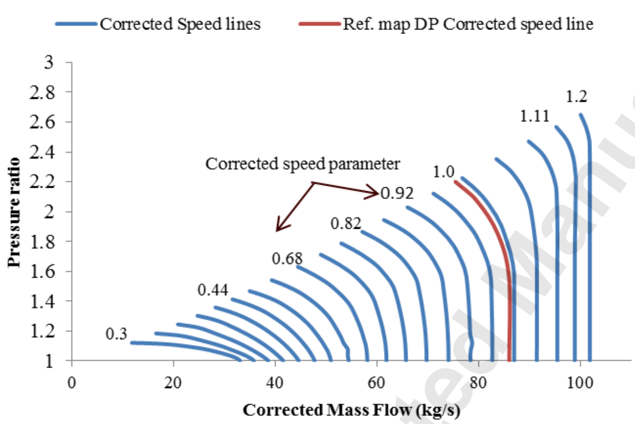

Fig. 3 Reference compressor map with the corrected mass flow against pressure ratio with air as working fluid

Based on the process flow description in Fig. 2, the first step is to obtain the design point parameters of the reference map (the reference map refers to the known gas turbine component map) and upload the map data characteristics points. The proceeding step is to derive the design point of the new component using available data points and the mathematical expressions described in this paper. Thus, the corrected parameters (corrected mass flow, corrected speed, etc) are calculated for the different working fluids in terms of Mach numbers for a known axial Mach number or inlet area using Eqs. (11), (13), (14), and (17). The purpose of calculating for each working fluid is to capture the thermodynamic properties of each fluid

The next step is to determine the scaling factors based on the reference map design point selected and the design point of the case study NPP, specifically the component in question. It infers that the corresponding data points have to be adapted from the reference map to create new component map data points by using the calculated scaling factors of Eqs. (5), (12), (15), and (18). The final step is to plot the new component map using the data points obtained. Figure 3 is a description of the reference map for the compressor. For the purpose of clarity, the reference map characteristic was based on air as working fluid.

The scaling factor for the corrected mass flow is given as:

$$CMSF = \frac{(CMF_{cs})_{DP}}{\left(CMF_{map}\right)_{DP}} \tag{5}$$

Where, $(CMF_{cs})_{DP}$ is the corrected mass flow of the case study NPP at the design point. $\left(CMF_{map}\right)_{DP}$ is the corrected mass flow of the reference map at the design point. The corrected mass flow is expanded to include the gas properties:

$$CMF = \left(\frac{W\sqrt{\theta}}{\delta} \times \sqrt{\frac{R}{\gamma}}\right) \tag{6}$$

Rewriting this relationship in terms of axial Mach number

$$W = \rho AV = \frac{P}{RT} AM_x\sqrt{\gamma RT} = \frac{PAM_x\sqrt{\gamma}}{\sqrt{RT}} \tag{7}$$

Using the static gas properties

$$P_t = P_s\left[1 + \left(\frac{\gamma - 1}{2}\right) M_x{}^2\right]^{\frac{\gamma}{\gamma - 1}} \tag{8}$$

$$T_t = T_s\left[1 + \left(\frac{\gamma - 1}{2}\right) M_x{}^2\right] \tag{9}$$

Combining Eqs. (7), (8) and (9) gives:

$$W = \frac{PAM_x\sqrt{\gamma}}{\sqrt{RT}\left[1 + \left(\frac{\gamma - 1}{2}\right) M_x{}^2\right]^{\frac{\gamma+1}{2(\gamma-1)}}} \tag{10}$$

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Rearranging the expressions in terms of corrected mass flow becomes:

$$CMF = \left(\frac{W\sqrt{\theta}}{\delta}\right) = \sqrt{\frac{\gamma}{R}} * AM_x \left[1 + \left(\frac{\gamma - 1}{2}\right) M_x{}^2\right]^{\frac{\gamma+1}{2(\gamma-1)}} \tag{11}$$

In the case of Eq. (11), either the inlet flow area or the axial Mach number of the turbomachinery component is known to carry out the analysis. The scaling rule is based on the equal flow axial Mach number for the different working fluid and equal static flow properties.

To modify the component physical geometry, the corrected mass flow can be calculated using Eq. (6); for working fluids other than the original working fluid, the use of fixed inlet geometry allows the corrected mass flow to be derived in terms of Mach number as shown in Eq. (11).

Similarly, the scaling factor for the pressure ratio is given as:

$$PRSF = \frac{(PR_{DP} - 1)}{(PR_{DPmap} - 1)} \tag{12}$$

Where, PR_{DP} is the design point of the focus NPP engine. PR_{DPmap} is the pressure ratio of the reference map at the design point.

The pressure ratio can also be expanded in terms of axial Mach number, gamma(γ), and the component efficiency to give compressor pressure ratio as:

$$PR_c = \left[\frac{(\gamma - 1)M_x{}^2 \eta_c}{\left(1 + \left(\frac{\gamma - 1}{2}\right) M_x{}^2\right)} + 1\right]^{\frac{\gamma}{\gamma-1}} \tag{13}$$

Similarly, for the turbine:

$$PR_t = \left[1 - \frac{(\gamma - 1)M_x{}^2}{\left(1 + \left(\frac{\gamma - 1}{2}\right) M_x{}^2\right)\eta_t}\right]^{\frac{-\gamma}{\gamma-1}} \tag{14}$$

Where, M_x is the NGV inlet Mach number

The speed scaling factor is expressed as:

$$CSSF = \frac{(CS_{cs})_{DP}}{(CS_{map})_{DP}} \tag{15}$$

Where the corrected speed (CS) is given by:

$$CS = \left(\frac{N}{\sqrt{\theta R \gamma}}\right) \tag{16}$$

Since corrected speed is proportional to the circumferential Mach number, it can be rewritten in terms of circumferential Mach number as:

$$CS = \left(\frac{N}{\sqrt{\theta R \gamma}}\right) = \frac{M_c \sqrt{\gamma R}}{\sqrt{\left(1 + \left(\frac{\gamma - 1}{2}\right) M_x{}^2\right)}} \tag{17}$$

The component efficiency scaling factor is obtained from:

$$\eta_c SF = \frac{(\eta_c)_{DP}}{(\eta_c)_{DPmap}}, \eta_t SF = \frac{(\eta_t)_{DP}}{(\eta_t)_{DPmap}} \tag{18}$$

The map data points scaled is obtained with the following expressions in Eqs. (19) – (23).

The scaled compressor pressure ratio is given as [15]:

$$PR_c = \left[\frac{\eta_{Dp}(\gamma_{Dp} - 1)\left(1 + \left(\frac{\gamma_{map} - 1}{2}\right) M_x{}^2\right)}{\eta_{map}(\gamma_{map} - 1)\left(1 + \left(\frac{\gamma_{Dp} - 1}{2}\right) M_x{}^2\right)} \left(PR_{cmap}{}^{\frac{(\gamma_{map}-1)}{\gamma_{map}}} - 1\right) + 1\right]^{\frac{\gamma_{Dp}}{(\gamma_{Dp}-1)}} \tag{19}$$

Similarly, the turbine pressure ratio is expressed as:

$$PR_t = \left[1 - \frac{\eta_{Dp}(\gamma_{Dp} - 1)\left(1 + \left(\frac{\gamma_{map} - 1}{2}\right) M_{NG}{}^2\right)}{\eta_{map}(\gamma_{map} - 1)\left(1 + \left(\frac{\gamma_{Dp} - 1}{2}\right) M_{NG}{}^2\right)} \left(1 - PR_{tmap}{}^{\frac{(1-\gamma_{map})}{\gamma_{map}}}\right)\right]^{\frac{-\gamma_{Dp}}{(\gamma_{Dp}-1)}} \tag{20}$$

The scaled mass flow is obtained using the expression in Eq. (21).

$$W = \frac{\sqrt{\gamma_{Dp} R_{map}} \left(1 + \left(\frac{\gamma_{map} - 1}{2}\right) M_x{}^2\right)^{\frac{(\gamma_{map}+1)}{2(\gamma_{map}-1)}}}{\sqrt{\gamma_{map} R_{Dp}} \left(1 + \left(\frac{\gamma_{Dp} - 1}{2}\right) M_x{}^2\right)^{\frac{(\gamma_{Dp}+1)}{2(\gamma_{Dp}-1)}}} * W_{map} \tag{21}$$

The scaled component efficiency is expressed as:

$$\eta_c = \eta_c SF * \eta_{c_{map}}, \ \eta_t = \eta_t SF * \eta_{t_{map}} \tag{22}$$

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The scaled corrected speed is expanded as:

$$CS = \frac{\sqrt{\gamma_{Dp} R_{Dp} \left(1 + \left(\frac{\gamma_{map} - 1}{2}\right) M_x{}^2\right)}}{\sqrt{\gamma_{map} R_{map} \left(1 + \left(\frac{\gamma_{Dp} - 1}{2}\right) M_x{}^2\right)}} * N_{map} \quad \textbf{(23)}$$

The above process was modeled using the in-house tool designed by the authors and used to simulate the case study results presented in Fig. (4) – (7). During the map scaling analysis, the axial Mach number was assumed to be 0.45; the compressor inlet area of the reference map was calculated as a result. For the turbine, the NGV Mach number and throat area are usually obtained from the choked flow area in the map. However, the turbine axial Mach number was also assumed to be 0.45. The compressor inlet temperature and pressure were given as 288.15K and 101325Pa respectively. The turbine entry temperature is given as 1100K and the gamma (γ) properties for the fluid at this temperature were given as 1.352 for air, 1.183 for carbon dioxide, 1.36 for nitrogen and 1.666 for helium. The compressor inlet area was obtained as 0.8668 using Eq. (7).

Table 3 Summary of component parameters scaled from the reference map

Components Details		Ref. map	He	CO_2	N_2
Compressor	Pressure ratio	2.070	2.310	2.081	2.142
	Actual mass flow kg/s	176.00	70.535	208.89	172.523
	Corr. mass flow kg/s	79.680	31.728	94.580	78.113
	Isen. efficiency	0.83	0.88	0.88	0.88
	Actual speed rpm	3600	10433	2814	3652
	Corrected speed	179.6	520.48	140.45	182.11
	Working fluid	air	helium	CO_2	nitrogen
Turbine	Pressure ratio	2.00	2.269	1.888	2.025
	Actual mass flow kg/s	176	70.405	208.56	172.128
	Corr. mass flow kg/s	79.218	31.687	93.898	78.075
	Isen. efficiency	0.88	0.88	0.88	0.88

Table 4 Summary of the scaling factor for a new component map of each fluid

Components Details		He SF	CO_2 SF	N_2 SF
Compressor	Pressure ratio	1.224	1.015	1.067
	Actual mass flow	0.401	1.190	0.980
	Corr. mass flow	0.401	1.190	0.980
	Isen. efficiency	1.060	1.060	1.060
	Actual speed	2.898	0.782	1.014
	Corrected speed	2.898	0.782	1.014
	Working fluid	helium	CO_2	nitrogen
Turbine	Pressure ratio	1.269	0.888	1.025
	Actual mass flow	0.400	1.185	0.978
	Corr. mass flow	0.400	1.185	0.978
	Isen. efficiency	1.000	1.000	1.000

RESULTS AND DISCUSSIONS

The results of the turbomachinery component scaling using the different fluid properties of a Gen IV closed gas turbine NPP are presented in Tables 3 and 4. Mass flow and pressure ratio conditions for carbon dioxide increased by 18.6% and 0.53% respectively when the reference fluid is air. This can be explained by the variation of gamma (γ) and R for a constant inlet annulus area and Mach number. In addition, the rotational speed decreases by ~22% because of the density of carbon dioxide compared with air. A similar pattern is also seen in the turbine map. A mismatch in the scaling rule for this study is represented by the variation in the exit area of the components.

For nitrogen, the similarities with air explain why its scaling factor is close to 1. This makes it easy to scale the map from air to nitrogen.

The study denotes that the closer the scaling factor is to 1, the more reasonable the generated maps data points for the different working fluids. Nonetheless, not having a value close to 1 does not necessarily imply that the scaled map will give a poor performance result [18,19]. With regard to helium, the rotational speed is increased by 189%. This increase will be compensated in a compact number of stages and length of the physical gas turbine component, with a compromise on the blade tip speed. This indicates that scaling will actually that the physical turbomachinery has to be modified as it is not possible to scale from air to helium for a fixed Mach number and inlet area. The scaling factor for the efficiencies remained almost constant because detailed losses were not considered in the analysis.

Fig. (4) – (6) shows the new component maps for each working fluid selected in the study, which can be adopted for off-design calculations. In Fig. (7) the design point speed lines for each working fluid component were superimposed on the reference map to give a clear variation on the extent of movement of speed lines from the reference component map design point to the scaled new design point for the various working fluids. The helium design point speed line drastically moved leftward as a result of its thermodynamic properties (gamma and gas constant). Its specific heat capacity is five times larger than that of air, which accounts for the significant shift. Also, the scaling factor obtained for air and helium was 0.4.

For the turbine component maps, there was slight variation than expected. This is due to changes in the gamma as temperature changes. The gamma properties used were 1.352 for air, 1.183 for carbon dioxide, 1.36 for nitrogen and 1.666 for helium.

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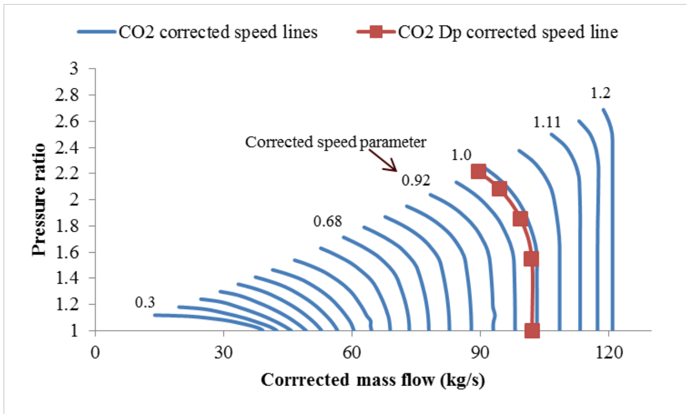

Fig 4 Scaled component map for carbon dioxide derived from the air working fluid reference map

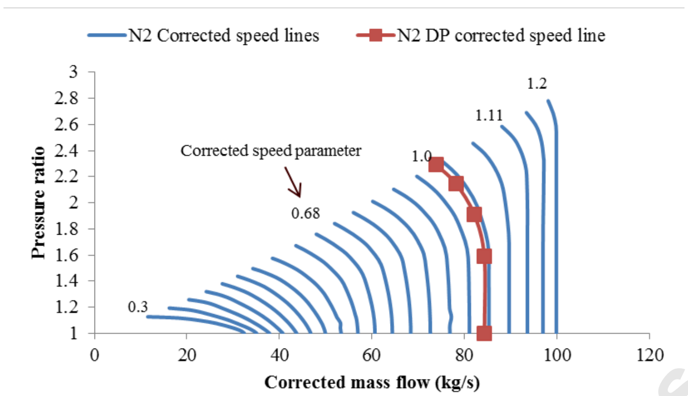

Fig. 5 Scaled component map for nitrogen derived from the air working fluid reference map

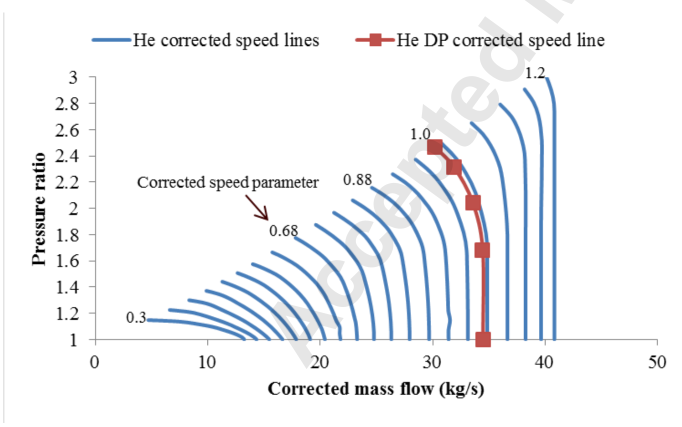

Fig. 6 Scaled component map for helium derived from the air working fluid reference map

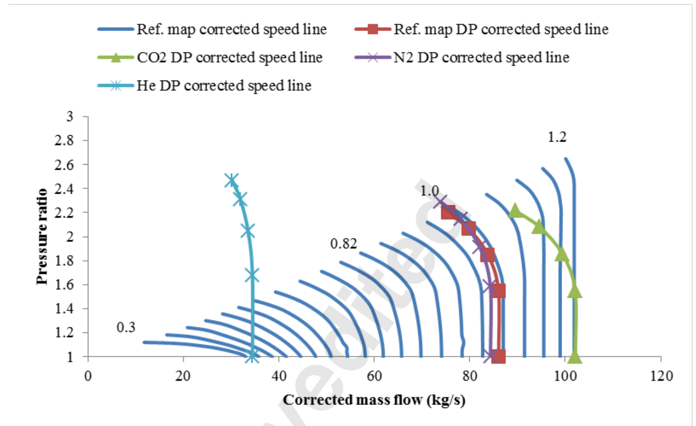

Fig. 7 Design point speed lines of new component maps for each working fluid superimposed on the air working fluid reference map

CONCLUSION

This paper documents a multi-fluid scaling technique which was utilised for selected gas turbine component maps. The reference point map adopted air. The scaled maps were for helium, carbon dioxide, and nitrogen for a fixed inlet area and axial Mach number. The scaling factors obtained were dependent on each characteristics data point and the properties of the working fluid selected for this study. The scaling factor allows for more calculations of the off-design points, where the Nuclear Power Plant (NPP) can operate at equilibrium. The main drawback of the scaling approach is that it requires more detailed information on the reference component map such as the inlet area and Mach number. The following conclusions can be drawn from the analysis:

- The scaling method adopted employs a holistic evaluation of the influence of the selected fluid properties on the component map characteristics from a physics point of view
- The scaling method also allows for theoretically scaling of the existing map to take place using similar or different working fluids without carrying out a full experimental test or repeating the whole design and development process.
- Scaling components with working fluids of different properties (γ, C_p, R) may not seem to be fully realistic without modifying the physical component
- The result presented in Fig. (7) shows that as gamma (ratio of specific heat capacities) increase farther away from the reference map design point, the scaling factor moves away from unity, hence, scaling for fluids with seemingly close gas properties can be better achieved with an accurate performance at off-design points.

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