TECHNICAL NOTE

The Wells air turbine subjected to inlet flow distortion and high levels of turbulence

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Introduction

Turbomachines are generally sensitive to the inlet flow conditions such as the distortion of inlet velocity profile and turbulence. The effect of inlet flow distortion is to degrade the performance, whereas turbulence levels up to 3% may actually improve the performance (see, for example, Refs 1 and 2).

The Wells self-rectifying air turbine[3], which is ideally suited for energy conversion in wave energy devices of the oscillating water column type, may have a distorted velocity profile at the inlet due to bends[4] (Fig 1) and may operate at high levels of turbulence at the inlet. This turbine has a characteristic feature which is significantly different from most turbomachines: the absolute velocities of the air flow are only fractions of the relative air flow velocity at entry to the turbine blades.

This paper presents investigations of the effect of inlet flow distortion and turbulence on the performance of a Wells turbine.

Test facility, model and instrumentation

The test facility was of a unidirectional air flow rig consisting of a settling chamber with screens, a contraction and a 0.21 m diameter test section connected to the suction end of a centrifugal fan (Fig 2). The rotors had a tip diameter $D_t = 0.026$ m and hub to tip ratio of 0.62. The turbine rotor had a built-in optical rotary transducer (Type ASL DORT 6) for torque and speed measurements. A calibrated orifice plate was mounted at the fan outlet. Pressure orifices were located circumferentially and at several stations axially on the rotor casing for pressure measurements upstream and downstream of the rotor. There were 8 circumferential orifices, which were equispaced around the circumference. The axial stations were 25 mm apart. The pressures were measured by a low pressure transducer (Type FC40). The inlet flow to the turbine was altered by the introduction of several devices: an orifice (Fig 3(a)), vertical grids (Fig 3(b)), a plate with square holes (Fig 3(c)) and an asymmetrical orifice (Fig 3(d)). The devices were positioned at 330 mm upstream of the rotor. The effect of the devices was to create a pressure gradient in both the axial and radial directions. However, the axial pressure gradients were small at a distance of 100 mm upstream of the rotor, indicating that the flow was very nearly settled. The pressure drop across the rotor was based on pressure measurements at stations 100 mm upstream and downstream of the rotor. The turbulence at the inlet was measured by a DISA 55M anemometer with a Type 55P probe. The details of the test conditions are given in Table 1.

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Results and discussion

The effect of inlet turbulence on the efficiency of a Wells turbine can be observed from Fig 4 where the variation of efficiency η with the flow coefficient ϕ_t are shown for three levels of turbulence (ϕ_t is proportional to the inlet flow angle). The average blade chord Reynolds number during the tests was $Re = 2.6 \times 10^5$. A large change in turbulence level Tu (0.4→6.7%)

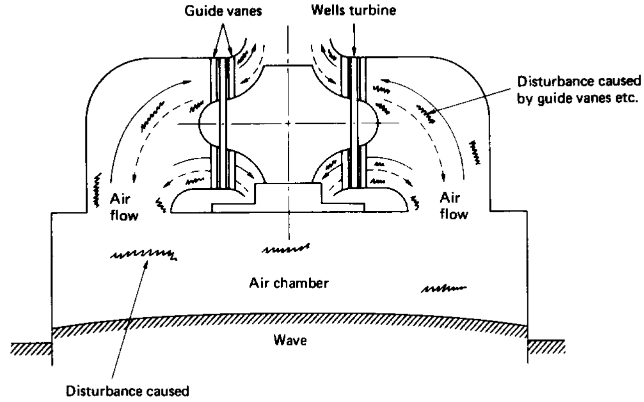

Figure 1 Set-up of Wells turbine with bends

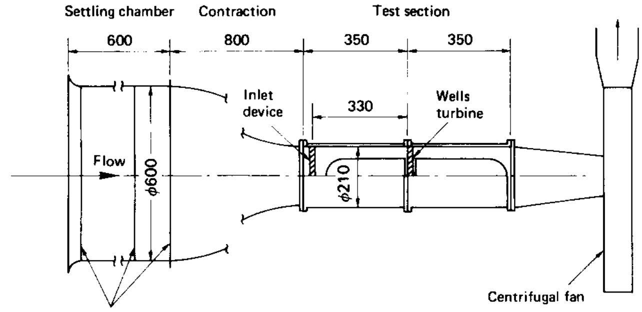

Figure 2 Test rig. All dimensions: mm

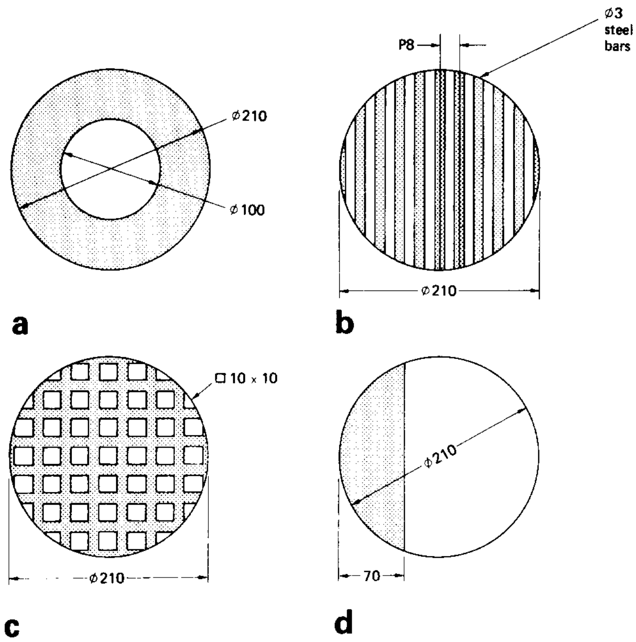

Figure 3 Inlet devices. Open flow area is unshaded. All dimensions: mm

Table 1 Test conditions

Airfoil	σ_t	Tu (%)
NACA 0021	0.4	0.4, 0.9, 1.3 3.2, 6.7
h=0.62 l=0.065 m	0.6	0.2, 7.9

produces only a small change in the turbine peak efficiency (0.64→0.66). The major effect appears to be the postponement of stall (0.24→0.3). It can be argued that the effect observed here is primarily the turbulence effect, and that any distortion of flow at the inlet on account of a device would have reduced the efficiencies and stall angle. The small variations in efficiencies in spite of large changes in the inlet turbulence level could be because, for the Wells turbine, the tangential velocities of the rotor are much larger than the absolute inlet air flow velocities, and therefore the turbulence levels relative to the blades are small. Typically, for the Wells turbine operating at a flow coefficient $\phi = 0.2$, the relative turbulence intensity is one-fifth of the inlet turbulence intensity. For a Wells turbine in oscillating air flow the postponement of stall associated with the increase in turbulence levels would increase the average cyclic efficiency.

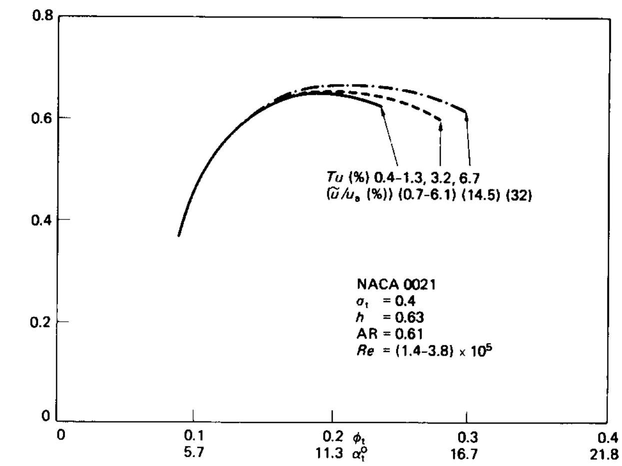

Figure 4 Effect of inlet turbulence on the efficiency of Wells turbine

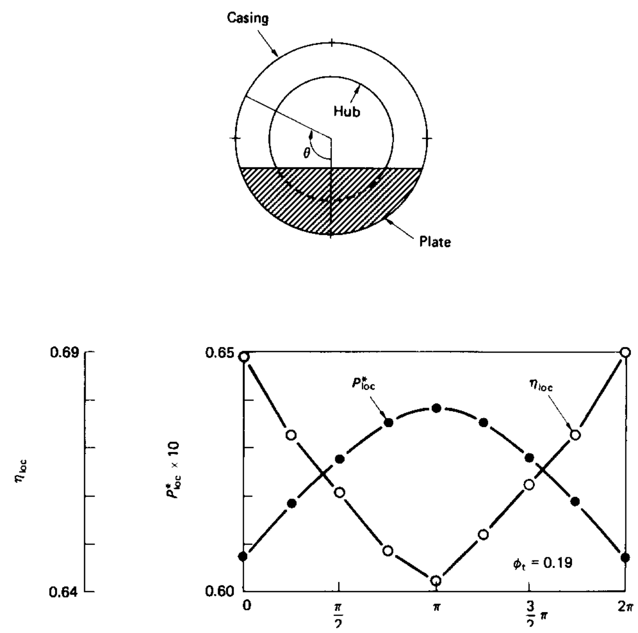

Figure 5 Effect of inlet distortion

The effect of inlet distortion can be seen from Fig 5. The distortion of flow at the inlet was created by the asymmetric orifice (Fig. 3(d)). The distortion of flow resulted in a circumferential variation of static pressures at the inlet to the turbine, resulting in different values of pressure drops and efficiencies depending on the pressure used in the calculations. The values of peak efficiencies ranged from 64% to 69%. The

Notation

AR	Aspect ratio $\equiv b/l$
b	Span of blade $\equiv D_t(1-h)/2$
D_t	Tip diameter
h	Hub to tip ratio
l	Chord length
n	Number of blades
p^*	Pressure coefficient $\equiv \Delta p/4\rho U_t^2$
Q	Flow rate
Re	Reynolds number $\equiv U_t l/\nu$
T	Torque
Tu	Turbulence level at maximum efficiency point $\equiv \tilde{u}/W_t$
$\tilde{u}$	rms value of velocity fluctuation
u_a	Axial velocity
U	Tangential velocity
W	Relative velocity $\equiv u_a^2 + u^2$
α	Angle of incidence
Δp	Pressure drop across rotor
η	Efficiency $\equiv \omega T/(\Delta p Q)$
ϕ	Flow coefficient $\equiv u_a/U_t$
ν	Kinematic viscosity
ρ	Density of air
σ	Solidity $\equiv nl/\pi D_t(Hh)$
ω	Angular velocity of the rotor

Subscripts

loc	Local
t	Tip

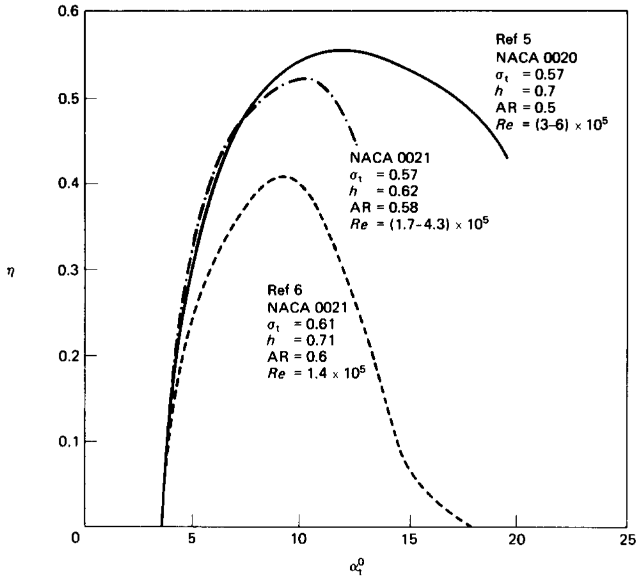

Figure 6 Reynolds number effect

peak efficiency based on the average pressure based on the mean of the wall static pressure measured around the circumference at the inlet was calculated to be 65%, and this is very close to the peak efficiency obtained with no inlet flow distortion (Fig 4). Thus, it could be argued that large distortion of flow at the inlet produces only a small relative distortion to the blades and, therefore, only small changes in the performance of a Wells turbine.

The turbulence effects cannot be separated from the Reynolds number effect (scale effect). In this context it is interesting to compare the performance of the Wells turbine tested at three different facilities (and possibly at different turbulence levels) at different Reynolds numbers. The results of experiments performed at Saga University[5], Queen's University and Tokyo University[6] are shown in Fig 6. The corresponding blade chord Reynolds numbers are 4.5×10^5, 3×10^5 and 1.4×10^5, respectively. The performance of the Wells turbine is very sensitive to scale effects, as can be seen from this figure. This is associated with the Reynolds number sensitivity at low Reynolds numbers of the NACA 4-digit profiles. At low Reynolds numbers, the changes with Reynolds number of both the peak efficiency and stall angle are considerably larger than those due to turbulence.

Conclusions

Experimental investigations were performed to study the effect of inlet turbulence and flow distortion on the performance of the Wells turbine. It is concluded that significantly large levels of inlet turbulence and flow distortions are necessary for them to have an appreciable effect on the Wells turbine performance. However, at low Reynolds number the efficiency and stall are very sensitive to Reynolds number.

References

1 Bry, P., Laval, P. and Billet, G. Distorted flow field in compressor inlet channels. *Trans. ASME*, July 1985, **107**, 782–791
2 Schlichting, H. and Das, A. On the influence of turbulence levels on the aerodynamic losses of axial turbomachines. In *Flow Research on Blading*, Dung, L. S. ed., Elsevier, 1970, 243–268
3 Raghunathan, S. and Tan, C. P. The aerodynamic performance of Wells turbine. *J. Energy* (*AIAA*), 1983, 7(3), 226–230
4 Ishii, S. et al. The report on operation and sea trial of the shore field type air turbine wave power generator. *AJMSTECTR 14* (1985), pp. 55–79
5 Inoue, M., Kaneko, K. and Setoguchi, T. Determination of optimum geometry of Wells turbine rotor for wave power generator (Part II). Presented at *Energy-Sources Technology Conference and Exhibition*, New Orleans, 1986
6 Suzuki, M., Arakawa, C. and Tagori, T. Fundamental studies on Wells turbine for wave power generator. *Bull. JSME*, 1984, **27**-231, 1925–1931