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3D Configuration of Shock Wave in Transonic Centrifugal Impeller Using 2D-PIV

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ABSTRACT

A particle image velocimetry (PIV) has major features of both laser velocimetries and flow visualization techniques. And it is very attractive owing to the feasibility of simultaneous and multipoint measurement. In the present experiment, a 2D-PIV was applied for a flow measurement in an inducer of a transonic centrifugal impeller. Velocity fields at five radii of the inducer were measured at two operating conditions of the compressor-peak-efficiency flow rate and the near-surge flow rate. The relative velocity fields were clearly visualized, and showed a shock wave on the suction surface of inducer blade. 3D configurations of a shock wave were obtained from the relative velocity fields measured using a 2D-PIV at five radii of the inducer.

INTRODUCTION

In a single-stage centrifugal compressor with four or more in pressure ratio, the relative velocity to the impeller and the absolute velocity at the diffuser vane exceed the speed of sound. That is, the generation of shock wave is unavoidable. A flow separation occurs due to interaction between the shock wave and the boundary layer. Thus, a slight change of operating condition causes significant performance degradation. A control of a shock wave is one option to improve compressor performance.

A laser-2-focus velocimetry has been successfully applied for a flow measurement in a transonic centrifugal impeller [Hayami et al., 1985]. The velocity field showed a shock wave on the suction surface of inducer blade [Hayami et al., 1987]. On the basis of the result, to reduce the intensity of a shock wave, a redesigned impeller with a little milder inducer blade camber from the leading edge to the inducer throat was tested, and then the critical flow of inducer stall of the impeller moved to lower flow with decrease in camber angle of inducer blade [Hayami et al., 1995]. That is, the configuration and/or the behavior of a shock wave at the inducer should be made clear more.

A particle image velocimetry (PIV) is very attractive for the ability to measure a velocity field. Thus, PIVs have been applied for measurements of flow in a subsonic axial compressor [Tisserant and Breugelmans, 1997], and of flow with a shock wave in a transonic axial compressor [Wernet, 2000].

In the preceding paper, a 2D-PIV was successfully applied for flow visualization in an inducer of a transonic centrifugal impeller, and phase-averaged velocity fields including a shock wave were visualized and discussed [Hayami et al., 2002a]. And, unsteady behaviors of a shock wave in the inducer were clearly visualized based on instantaneous velocity fields measured using a PIV [Hayami et al., 2002b]. In the present experiment, velocity fields at five radii of the inducer were measured using a 2D-PIV at two flow rates. The relative velocity fields with a shock wave were visualized. And 3D configurations of a shock wave were obtained from the relative velocity fields measured using a 2D-PIV, and were discussed in relation to effects of flow rates.

EXPERIMENTAL APPARATUS AND PROCEDURE

A transonic centrifugal compressor was tested in a closed loop with HFC134a gas. Figure 1 shows the meridional profile of the test compressor and the PIV system. The open shroud impeller had 15 main blades and 15 splitter blades with a backward sweep angle of 40 deg at the exit. The impeller diameter was 280 mm. The inducer tip diameter and the hub diameter were 172 mm and 80 mm, respectively. Downstream of the impeller was a diffuser consisted of two parallel walls, 9.4 mm apart from each other, and a low-solidity cascade with eleven vanes.

The present PIV system was based on a double-pulsed PIV with a frame straddling technique. As a light source, a Nd:YAG laser (Continuum Minilite II) with 25 mJ/pulse was used. The light sheet was generated using a light sheet projector [Hayami et al., 2002a] of 10 mm in outer diameter and 200 mm long, which was located at 370 mm upstream from inducer leading edges. The light sheet was 19 mm wide and 1.2 mm thick at the inducer. As a tracer particle, dioctyl phthalate (DOP) particles of about 0.6 μm in mean diameter were used. The tracer particles were generated using an aerosol atomizer (TSI Model 9306), and were supplied through a pipe of 5 mm in outer diameter, which was located at 300 mm upstream from the inducer leading edges. To observe the particles, a glass window of 16 mm in diameter was mounted on a shroud casing. Particle images were captured using a CCD camera with 1008 x 1016 pixels (KODAK MEGAPLUSE ES1.0) equipped with a lens (NIKON Micro Nikkor 105 mm f/2.8). The spatial resolution of the particle images was 22 μm/pixel. The images, 149 pairs in the present measurement, were stored in a PC through a frame-grabber board (EPIX PIXCI-D).

A fluid flow is periodic at a blade-passing frequency when a stationary measurement system is used for a flow measurement. Thus, a conditional sampling technique is required. A blade-passing signal was picked up using a non-contact displacement sensor (AEC GAP-SENSOR 5505) mounted on a shroud casing as shown in Fig. 1. The sampling rate of a pair of images was every 100 revolutions or about 3 Hz using a preset counter. A delay pulse generator was used so that the measurements could be performed at any impeller blade phase. A timing controller was used to control the laser and the camera. The time interval between double pulses was 2 μs.

Figure 2 shows the coordinate system. The origin is set to the inducer tip. The parameter m is the axial distance from the leading

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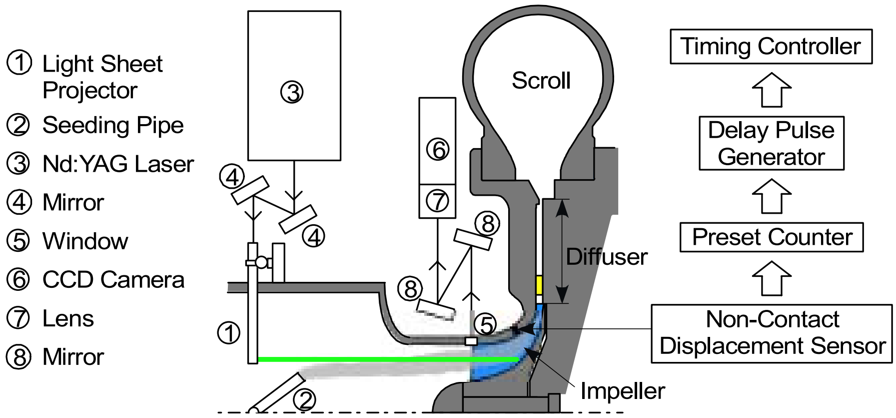


Fig. 1 Meridional profile of test compressor and PIV system.

edge of inducer, and z is the distance from the inducer tip. Tests were made every 0.1 in depth ratio, z/b, from z/b = 0.1 to 0.5. Here, b is the inducer blade height.

The instantaneous velocity vectors were evaluated based on a cross-correlation method with sub-pixel processing. The interrogation area was 31 x 31 pixels. And the phase-averaged velocity vectors were evaluated from 149 instantaneous velocity vectors based on the average-correlation method [Meinhart et al., 2000] with sub-pixel processing.

EXPERIMENTAL RESULTS AND DISCUSSIONS

The characteristic curves of the test compressor are shown in Fig. 3. The ordinate P_4/P_0 is the total pressure ratio, and the abscissa G/G^* is the ratio of the mass flow rate to the choked flow rate in the suction pipe. The parameter M_t is the corrected speed or the nominal Mach number based on the inducer tip speed and the inlet total temperature. Tests were performed at two operating conditions of the compressor-peak-efficiency flow rate (CP) and the near surge flow rate (NS) along the constant corrected speed line of M_t = 1.041. The rotor speed was about 18,100 rpm.

Figures 4 and 5 show the phase-averaged relative velocity vector fields at five radii of the inducer at CP and NS, respectively. The origin of the map is set to the blade leading edge of left hand side. An arrow indicates the relative flow direction, and a color indicates the magnitude of relative flow Mach number, M_r, based on the inlet total temperature. Here, the relative velocity vectors were calculated by vectorial subtraction of the absolute velocity vector evaluated directly from images and the peripheral velocity vector of the impeller. The local sound speed was about 157 m/s. The phase-averaged velocity fields were calculated from 149 instantaneous velocity fields. The high subsonic fluid flow is once accelerated along the blade suction surface, and then a shock wave is generated behind the supersonic zone. The supersonic zone gradually became narrower with increase in depth ratio at each flow rate. Beyond the mid span of blade height or z/b = 0.5, no clear shock wave was recognized at either flow rate. The figures show that the location of a shock wave moves upstream from CP to NS or with decrease in flow rate. And the intensity of a shock wave became stronger with decrease in flow rate.

Figure 6 shows the contour maps of relative flow Mach number at the leading edge of inducer blade at CP and NS. Here, SS and PS in the figures are the suction surface and pressure surface of inducer blade, respectively. At either flow rate, the location of a shock wave was almost straight in the depth direction. The sharp change in relative flow Mach number is recognized especially at the inducer tip at NS. Figure 7 shows the contour maps of incidence angle, i_1, at the leading edge of inducer blade. There is a large change in incidence angle at NS in comparison to CP. And the incidence angle at NS became high positive especially behind a shock wave or at the pressure surface.

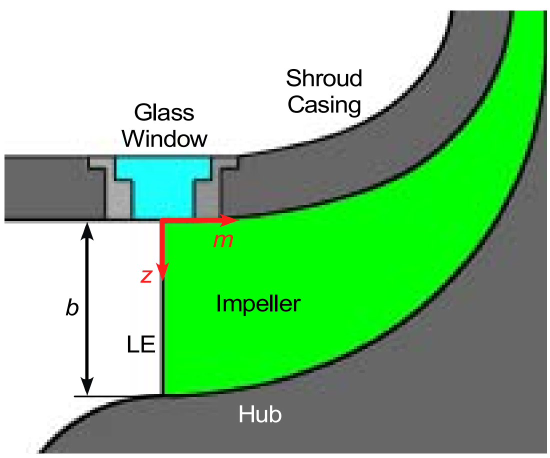


Fig. 2 Coordinate system.

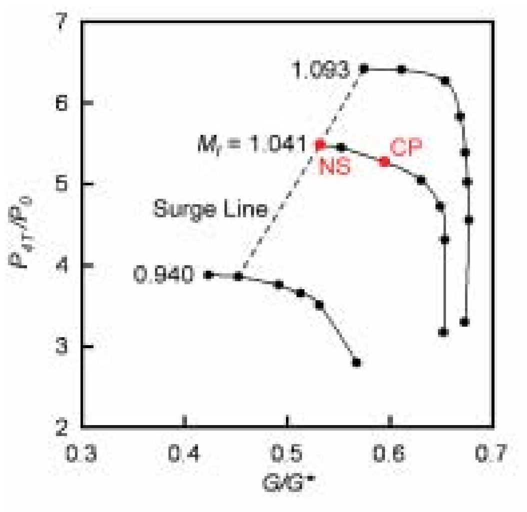
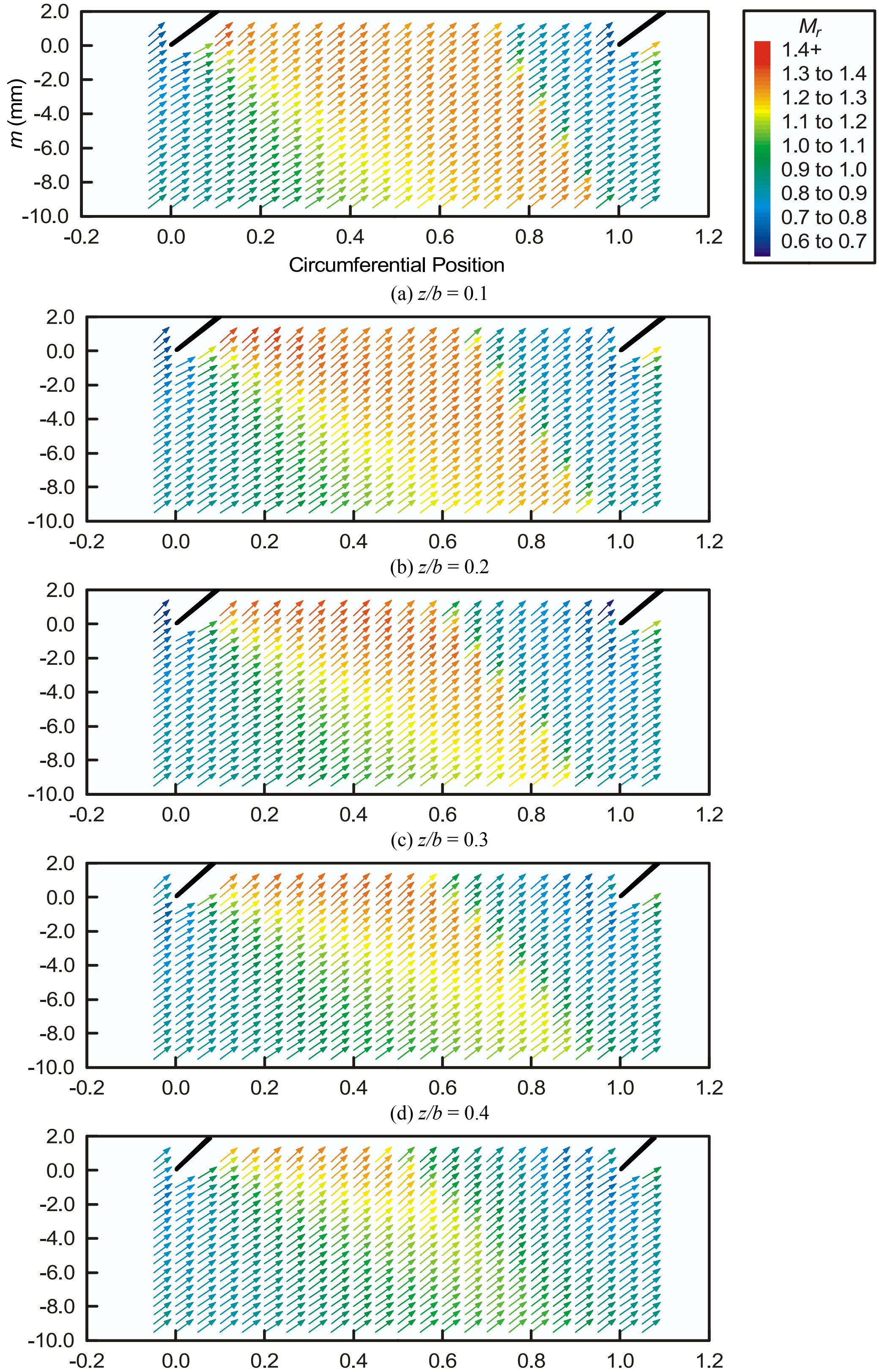


Fig. 3 Characteristic curves of test compressor.



(a) $z/b = 0.1$

(b) $z/b = 0.2$

(c) $z/b = 0.3$

(d) $z/b = 0.4$

(e) $z/b = 0.5$

Fig. 4 Phase-averaged relative velocity vector fields at CP.

CONCULUTION

A 2D-PIV was applied for a flow measurement in an inducer of a transonic centrifugal impeller. Velocity fields at five radii of the inducer were measured at two flow rates. 3D configurations of a shock wave at two flow rates were obtained from relative velocity fields measured using a 2D-PIV at five radii of the inducer. The supersonic zone gradually became narrower with increase in depth ratio. With decrease in flow rate, the location of a shock wave moves upstream, and the intensity of a shock wave became stronger. The location of a shock wave was almost straight in the depth direction at the leading edge of inducer blade. At NS, the gradient of relative flow Mach number is sharp especially at the inducer tip,

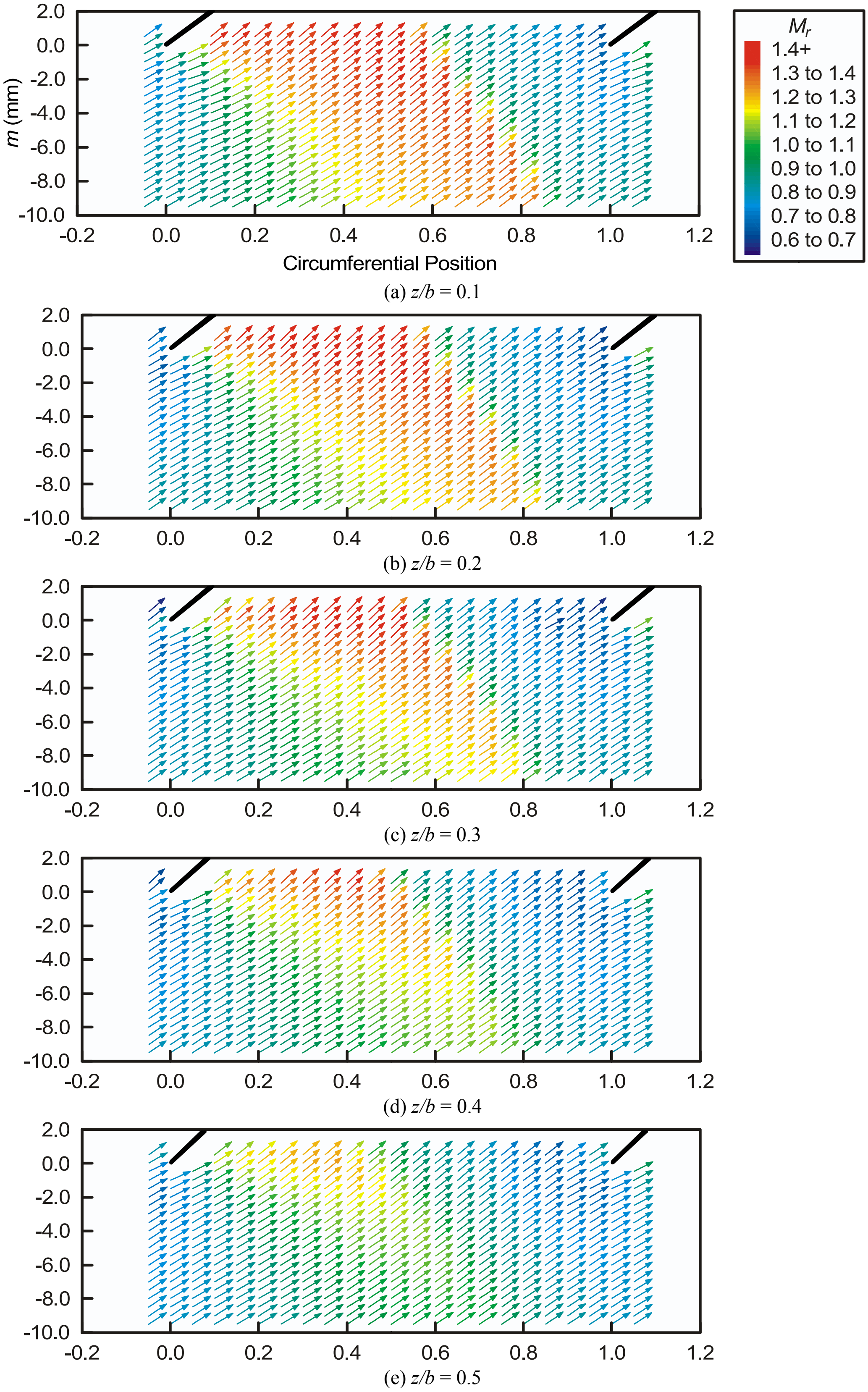


Fig. 5 Phase-averaged relative velocity vector fields at NS.

and the incidence angle became high positive especially behind a shock wave.

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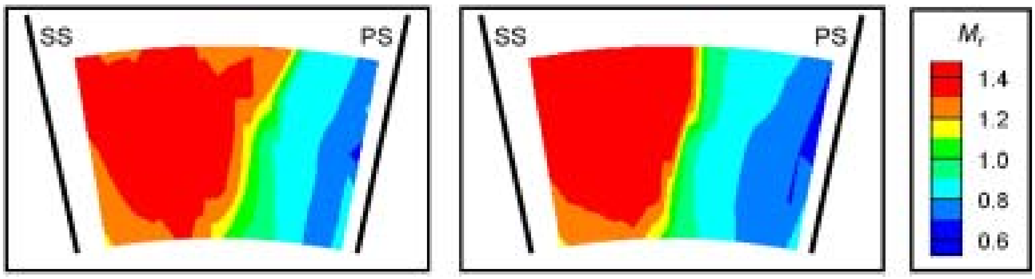
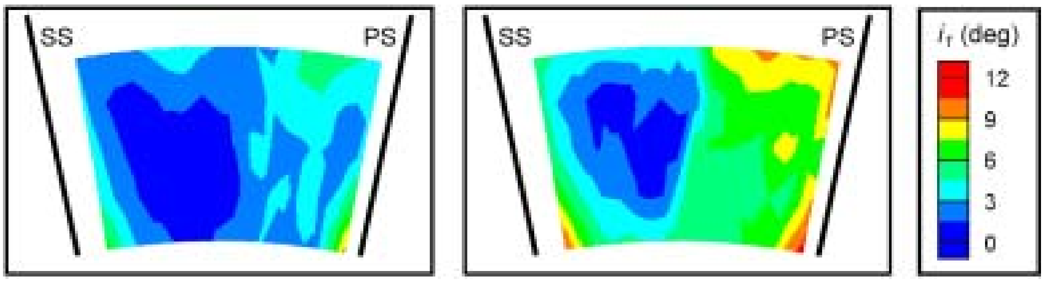


(a) CP (b) NS

Fig. 6 Contour maps of relative flow Mach number at leading edge of inducer blade.



(a) CP (b) NS

Fig. 7 Contour maps of incidence angle at leading edge of inducer blade.

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