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Innovative Wind Flow Modifier Solutions for Improved Vertical Axis Wind Turbine Performance

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Abstract - Wind power has become more important as the world moves toward using cleaner, more sustainable energy sources. However, optimizing VAWT performance under these circumstances is difficult. An innovative method to improve VAWT performance in low wind profiles is the use of wind flow modifiers (WFMs). The effectiveness of a C-shaped rotor with a low aspect ratio is simulated. In addition, a series of tubes with progressively smaller inside diameters are stacked from wind input to outflow in the WFM model. Its efficacy in increasing wind speed is tested using an involute turbine. The maximum power coefficients for the drag force rotor and the lift force involute rotor are 0.071 and 0.22, respectively. Further, the maximum power coefficient of the suggested WFM with an involute rotor is significantly increased to a noticeable value of 0.397 at 5 m/s wind speed, which allows for effective design in the low wind profile region.

Keywords: - Wind energy, Turbines, Vertical Axis, Rotor, Blade

Introduction

Wind turbines, which convert the kinetic energy of wind into electricity, have become emblematic of this green energy revolution. Among the various types of wind turbines, the Vertical Axis Wind Turbine (VAWT) stands out as an innovative and promising design, particularly well-suited for low wind profiles. However, optimizing the performance of VAWTs in such conditions presents unique challenges. In this era of advancing computational capabilities and scientific modeling, the application of Wind Flow Modifier (WFM) modeling to

VAWTs for low wind profiles has gained considerable attention.

This interdisciplinary approach combines fluid dynamics, structural mechanics, and computational modeling to revolutionize the way we understand and harness wind energy. The quest for clean and sustainable energy sources has never been more critical, with the specter of climate change looming large and the depletion of finite fossil fuel reserves increasingly evident. Wind power has emerged as a formidable solution in this global effort to transition to renewable energy sources. Unlike traditional fossil fuels, wind energy offers an eco-friendly, inexhaustible, and scalable energy source. Wind turbines, designed to capture the kinetic energy of moving air, have proliferated across landscapes, both onshore and offshore, to tap into this immense potential.

Vertical Axis Wind Turbines (VAWTs) have garnered attention as a unique and promising approach to wind energy conversion. Unlike their Horizontal Axis Wind Turbine (HAWT) counterparts, VAWTs boast distinctive features such as a smaller footprint, lower noise levels, and suitability for decentralized applications. These attributes make VAWTs particularly appealing for urban environments and regions with low wind profiles. However, optimizing the performance of VAWTs in such conditions presents a complex engineering challenge.

Low wind profiles, often encountered in urban areas or regions with variable wind resources, demand a specialized approach to maximize energy capture. Conventional VAWT designs struggle to perform efficiently under these conditions due to lower wind speeds and increased turbulence near the ground. This limitation has led to the exploration of innovative solutions, one of which is the integration of Wind Flow Modifiers (WFMs).

Wind Flow Modifiers are devices or techniques employed to manipulate and control the wind flow around a wind turbine. Their primary objective is to enhance the aerodynamic performance of the turbine blades by mitigating the adverse effects of low wind profiles, such as blade stall and reduced rotor efficiency. The concept of using WFMs to optimize VAWT performance in low wind conditions represents a paradigm shift in wind turbine engineering, where traditional designs are augmented with state-of-the-art fluid dynamics and computational modeling.

The importance of WFM modeling for VAWTs in low wind profiles extends beyond the realm of energy production. It aligns with global efforts to increase the penetration of renewable energy sources into the grid, reduce greenhouse gas emissions, and promote sustainable development. Achieving higher efficiency and reliability in VAWTs under challenging wind conditions can significantly contribute to the broader renewable energy landscape and help address pressing environmental concerns.

This exploration of WFM modeling for VAWTs in low wind profiles serves as a comprehensive investigation into a burgeoning field at the intersection of aerodynamics, structural engineering, and computational science. Throughout this discourse, we will unravel the intricacies of VAWT operation, the unique challenges posed by low wind profiles, and the innovative techniques and technologies that underpin WFM modeling. We will delve into the theoretical foundations, computational methodologies, and realworld applications of WFMs, shedding light on the potential they hold for revolutionizing wind energy generation.

In the subsequent sections, we will embark on a journey through the multidisciplinary landscape of WFM modeling. We will begin by delving into the fundamentals of VAWT operation and the distinct advantages they offer in comparison to HAWTs. From there, we will explore the complex dynamics of wind flow in low-profile environments, uncovering the challenges that VAWTs face in such conditions. With a solid foundation in place, we will then transition to the heart of our discussion: the concept of Wind Flow Modifiers.

I.Proposed Rotor Model Geometry

The primary goal of this research is to design a rotor for VAWT suitable for usage in metropolitan locations with moderate wind speeds. The VAWT model proposes using a wind flow modifier (WFM) consisting of a stack of tubes of varied diameters called diffusers to increase the wind speed in such locations. An involute rotor blade with a wind flow modulator is presented as an alternative to the conventional H-type, 4-series NACA blades. Taking everything into account, our study focused on the following two configurations depending on the shape of the rotor.

- H-type Rotor with C-blade
- Involute rotor with a wind flow modifier

II.Results And Discussion

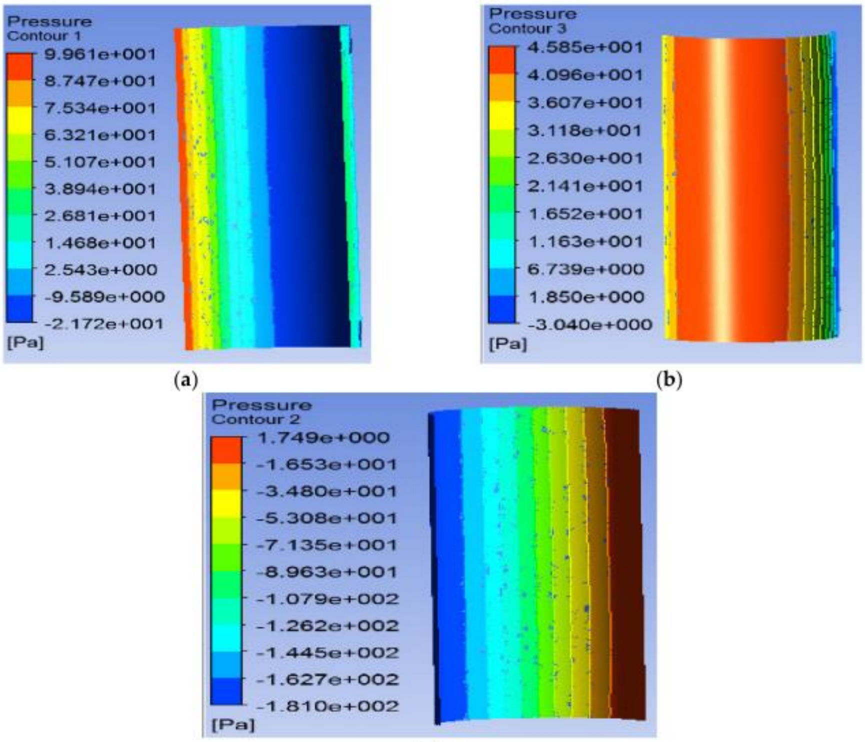
The effectiveness of the suggested setups at varying wind speeds is discussed below. Pressure changes on individual blades and the VAWT model are shown at a range of velocities, from 2 meters per second (m/s) at the cut-in speed to 24 m/s (m/s) at the cut-out speed. The resulting changes in pressure exert both drag and lift on the rotor blades. The suggested involute blades VAWT model may benefit greatly from the measurement of drag and lift force coefficients and associated forces. We also examine and contrast the electrical and mechanical properties of the blades and turbine model. An ideal three-bladed turbine meeting the aforementioned domain parameters and featuring sliding mesh rotor interfaces is simulated with a velocity intake of 2 m/s and a swept area scaled to 0.96 square meters. The next section discusses the outcomes obtained from the various setups.

H-type Rotor with C-blade

C-blade profiles are open to intake velocities along the -X axis. Also, the drag and lift forces produced on the blades are analyzed at an angular velocity of 60 rpm, which is equal to 5 m/s (the linear velocity for the comparable diameter). Since a three-blade turbine works best in this setup, we'll analyze the pressure and velocity output of each blade separately.

- **Individual Blade Performance**

According to the pressure differences seen on the C-blades, Blade 3 generates the most negative pressure (181 Pa) and produces the most drag. Figure 1 demonstrates how Blade 2 provides strong pressure on the +Z axis with low drag force. As can be seen in Figure 2, the drag force generated by Blade 3 is the highest, followed by Blade 1, and the net drag coefficient (Cd = 0.205) achieved is much more than the negative lift coefficient (Cl = 0.094). In addition, the drag force exerted by the C-shaped blades is sufficient to turn the turbine rotor at a speed of 60 revolutions per minute, yielding a drag-to-lift ratio of 2.181.



(a) (b)

(c)

Figure 1 C- shaped H- type pressure contours (a) Blade 1 (b) Blade 2 and (c) Blade 3

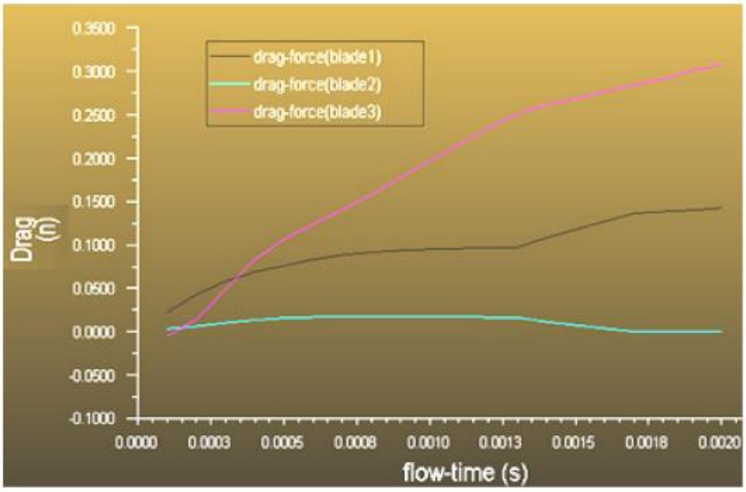


Figure 2 Drag characteristics (Cd)

- **Rotor Performance**

This section illustrates the C-blade's rotor performance at a wind velocity of 60 revolutions per minute. The primary goal of this study is to detect low-velocity wind turbines, as described in the preceding sections. The pressure and velocity changes, the velocity gradient between the intake and the turbine, and the momentum coefficient must be calculated.

As can be seen in Figure 3, a C-blade turbine's Blade 2 creates a high pressure of +99.6 Pa, while Blade 1 generates a low pressure of 21 Pa. As seen in Figure 4, this results in the most torque being applied to Blade 1's leading edge, where the velocity is the highest. However, as seen in Figure

5, the resulting drag forces lead the rotor to revolve counterclockwise, from Blade 2 to Blade 1. It demonstrates how lift forces are perpendicular to the direction of the wind and drag forces are parallel to the direction of the wind. The moment value, measured around the turbine's +Z axis of rotation, is extracted from the simulation results in order to investigate the blades' and turbine's torque characteristics. Figure 6 shows that at a little negative pressure, Blade 1 produced its maximum moment of 0.30. The other two blades, on the other hand, provide a negative momentum that acts to dampen the overall torque. This might be a major factor in why wind turbines that rely on drag force produce so little electricity.

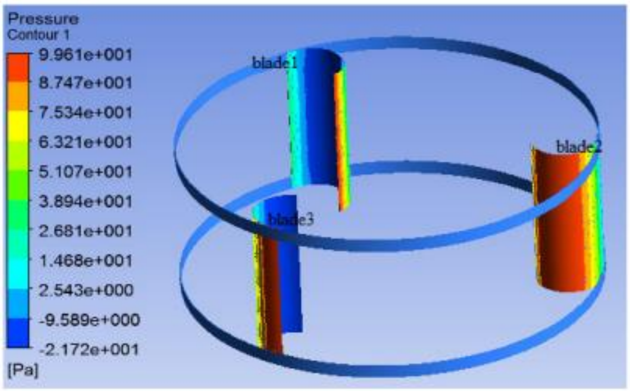


Figure 3 Pressure variation over the rotor

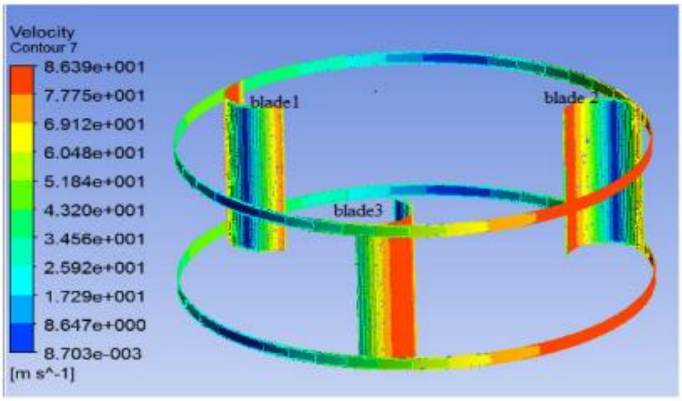
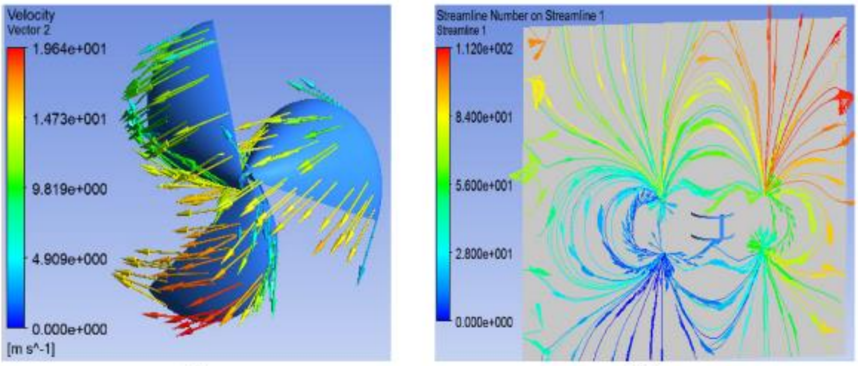


Figure 4 Velocity variation over the rotor



(a) (b)

Figure 5 (a) Lift and drag Forces; (b) velocity gradients

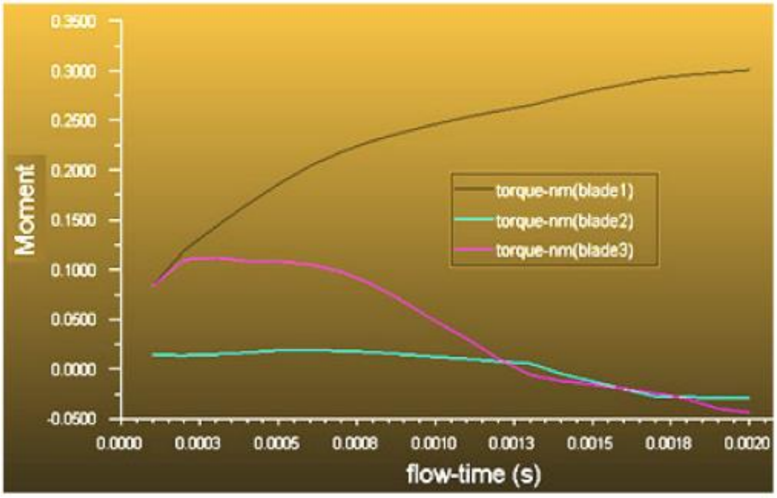
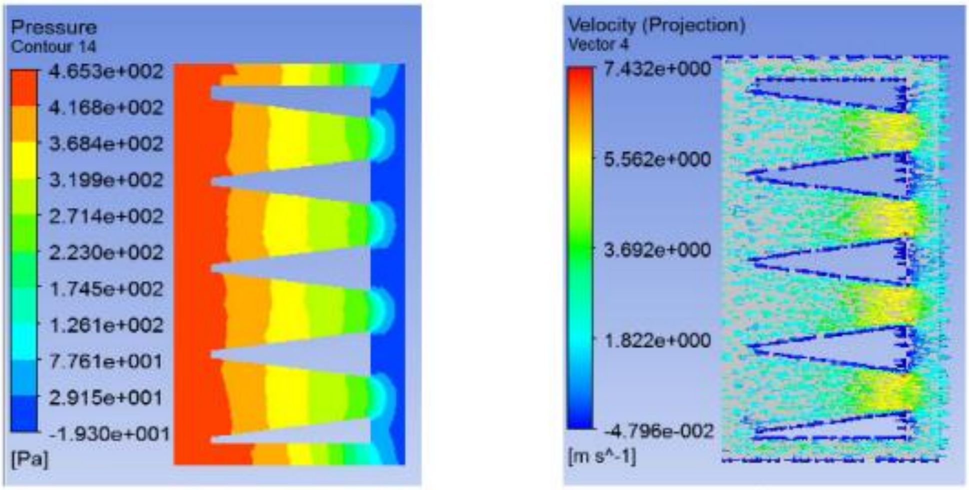


Figure 6 Blade momentum

Involute-Type Rotor with WFM

The WFM was built using a stack of 12 diffuser tubes (4 rows, 3 columns) with a diameter variation of around 2 times from input to exit. As can be seen in Figure 7a, the pressure varies from +465 to 19.3 Pa. With a velocity magnification ratio of 3.05, the pressure gradient in the diffuser tubes causes a change in velocity from around 1.822 m/s (at the intake) to 5.562 m/s (at the output). As can be seen in Figure 7b, it helps in generating more forces for the turbine. The extra advantages of this model are used in low wind profile locations, as seen by the shifts in velocity amplification from the intake to the exit of the diffuser tubes. The link between the condenser and the turbine in a thermal power plant is represented by this WFM and VAWT model.

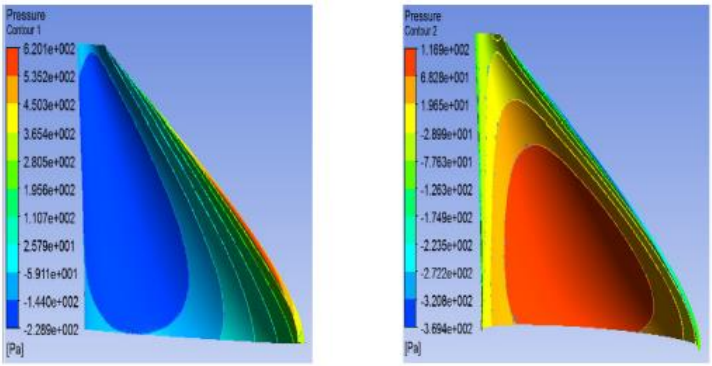


(a) (b)

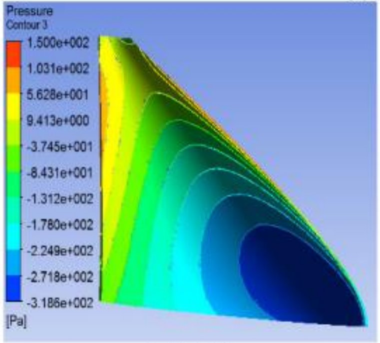
Figure 7 Pressure (a) and velocity (b) variations inside the diffuser tubes

- **Individual Blade Performance**

Figure 8 shows how the pressure differences on the involute blades are affected by the wind flow modifier (WFM). This setup is quite similar to instance 2, but with the wind flow modulator positioned between the intake and the turbine, rather than on the blade surfaces. In particular, Blade 1 provides a greater lift force than the other two blades and has heightened low-pressure fluctuations of 228 Pa. Table 1 shows that, in contrast to the prior situation, all three blades are equally contributing to lift forces. As a consequence, Blade 1 has a lift coefficient of approximately 0.3311, Blade 2 of about 0.3245, and Blade 3 of around 0.2278. When the WFM is oriented towards the wind, the lift-to-drag ratio increases to an impressive 18.84.



(a) Blade 1 (b) Blade 2



(c) Blade 3

Figure 8 Involute type with WFM pressure contours

Table 1 Lift and drag coefficients

Blade No	**Lift**	**Drag**
1	0.3311	0.0545
2	0.3245	0.0321
3	0.2278	−0.0415
Net rate	0.8832	0.0451

- **Rotor Performance**

As shown in Figure 9, the rotor equipped with WFM produces pressures of about +150 and -318 Pa at the high and low ends, respectively. In addition, the rotor experiences a velocity range of around 16.57 ms1, which, as shown in Figure 10, results in a larger torque rate than in earlier case studies.

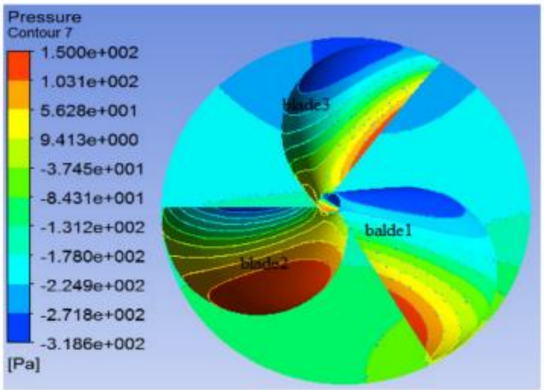


Figure 9 Pressure contour

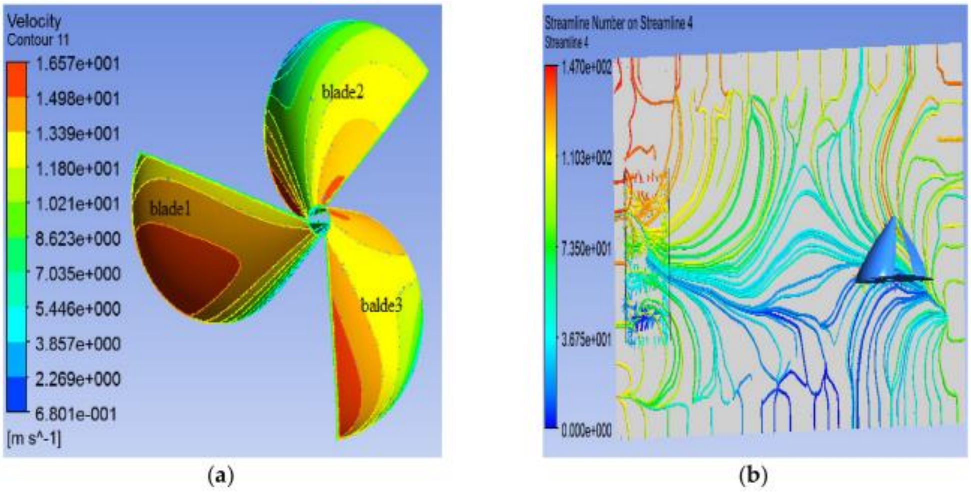


Figure 10 Velocity (a) and gradient (b) variations on involute blades with WFM

Figure 11 shows that compared to an involute rotor, the moment produced by the WFM-based rotor is 1.56 times more. The simulation results have been used to discuss the overall performance of all three setups. Improved performance is seen with the WFM-configured involute rotor.

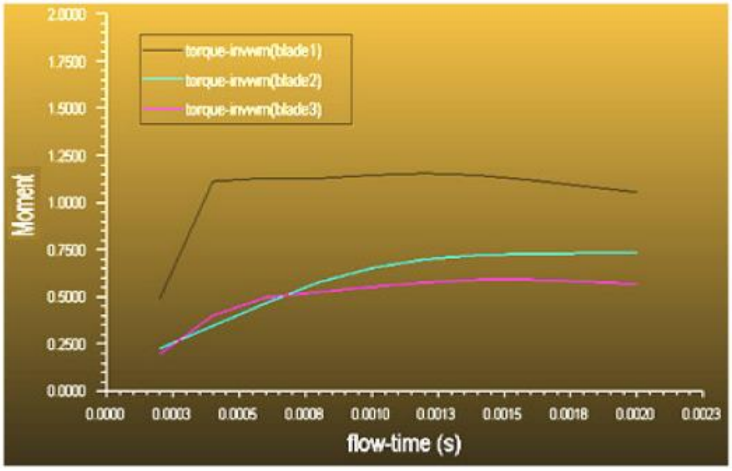


Figure 11 Blade momentum

III. Conclusion

Wind Flow Modifier modeling represents a transformative step in the evolution of wind energy technology. With continued dedication to research and development, WFMs can become a cornerstone of sustainable energy generation, contributing to a cleaner, more environmentally friendly future for generations to come. As we harness the power of the wind with greater efficiency and ingenuity, we pave the way toward a world powered by renewable energy, reducing our reliance on fossil fuels and mitigating the impacts of climate change.

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