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# Experimental investigation on mass flow rate measurements using fibre Bragg grating sensors

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**Abstract**. Flow measurement and control of cryogens is one of the major requirements of systems such as superconductor magnets for fusion reactors, MRI magnets etc. They can act as an early diagnostic tool for detection of any faults and ensure correct distribution of cooling load while also accessing thermal performance of the devices. Fibre Bragg Grating (FBG) sensors provide compact and accurate measurement systems which have added advantages such as immunity towards electrical and magnetic interference, low attenuation losses and remote sensing. This paper summarizes the initial experimental investigations and calibration of a novel FBG based mass flow meter. This design utilizes the viscous drag due to the flow to induce a bending strain on the fibre. The strain experienced by the fibre will be proportional to the flowrate and can be measured in terms of Bragg wavelength shift. The flowmeter is initially tested at atmospheric conditions using helium. The results are summarized and the performance parameters of the sensor are estimated. The results were also compared to a numerical model and further results for liquid helium is also reported. An overall sensitivity of 29 pm.$(g.s^{-1})^{-1}$ was obtained for a helium flow, with a resolution of 0.2 g.s-1. A hysteresis error of 8 pm was also observed during load-unload cycles. The sensor is suitable for further tests using cryogens.

## 1. Motivation

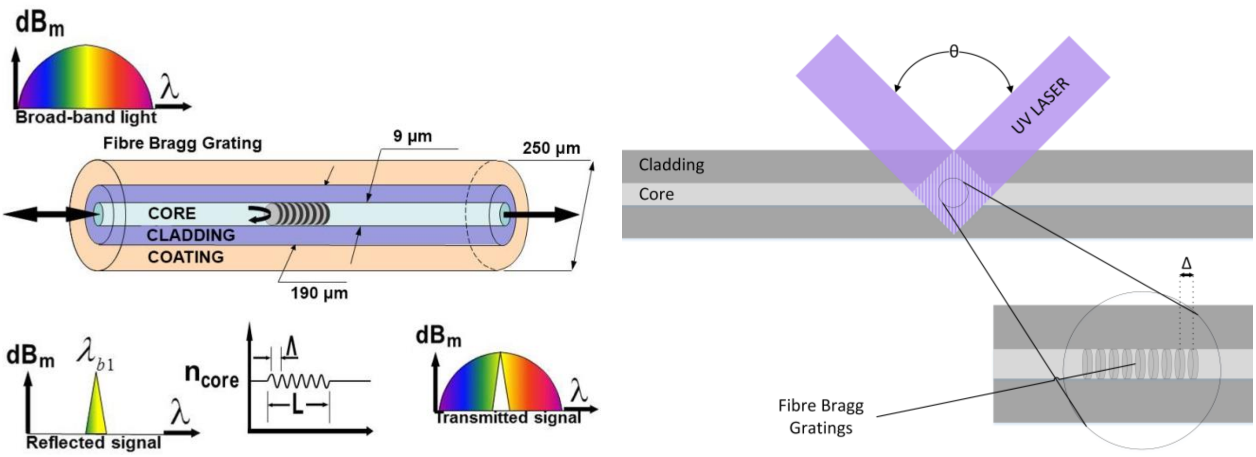
Current breakthroughs in cryogenics, such as those in areas of aerospace applications, superconductivity etc. demand advances in current instrumentation systems to suit the specific requirements of the application. In cryogenic rocket engines, due to the small size of the flow channels, a miniature sensor is preferred which can effectively monitor the flow rate in each individual channels without producing a high pressure drop. Similarly in case of applications such as cryoprobes, from cryosurgery applications, and micro coolers used in cooling of IR detectors presence of vibration is a serious issue. Many of the current flow measurement systems cannot operate with desired accuracy in presence of high magnetic fields, such as those present in the superconducting generators, helium cooled Magnetic Resonance Imaging (MRI) magnets etc [1]. Along with these, there are stringent measures that have to be taken into account during the material selection for the fabrication of the flow meters. The materials that are used must be compatible with the low temperatures involved and also the multiple insulation systems employed.

The traditional measurement techniques based on pressure drop across a body such as orifice meters, venturi tubes, laminar flow meters etc. are not much suited for many cryogenic applications. The pressure drop induced by them can cause cavitation and losses in the flow and thus can only be employed at the outlet of the system. Another common technique used in flow measurement is based on hot-wire anemometry. In simple terms, a specific amount of heat is introduced into the flow using a film or wire inserted into the flow regime. The change in temperature of the wire or at a point downstream to the wire is measured and the change in temperature gives an indication of the flow rate. While this method can be used at any section of the flow, it possesses the disadvantage that it introduces heat in to the system which can be critical in highly insulated cryogenic systems.

### *1.1. Fibre Bragg Grating (FBG) Sensor*

A fibre Bragg grating (FBG) is an optical element that is placed in an optical fibre, by means of creating a set of gratings at specific grating periods. The grating in this case is a part of the fibre with a refractive index different than the homogeneous domain.

A FBG sensor is introduced in an optical fibre by using inscribing or writing the grating profile using high power UV lasers [2]. A common method to do so is to allow two UV laser beams to intersect at a specific angle on an optical fibre (Figure 1(b)). The constructive and destructive interference of the UV will alter the bonding of doping elements in the fibre creating areas of varying refractive indices. Various other methods such as photo masking etc. can also employed. Recent researches have also lead to production of FBG sensors in polymer strands, negating the chances of fracture which is inherent with glass fibres. In this work, glass FBG sensors based on UV interference method are used.




(a) (b)

Figure 1 (a) Operation of FBG Sensor, (b) Interference method for fabrication of FBG sensor

The operation of the FBG sensor is shown in Figure 1(a). When a beam of broadband light is send through the fibre, the sensor reflects light of a specific wavelength while allowing all other wavelengths to pass through without distortion. In case of multiple sensors placed in a single fibre (multiplexing), the reflected wavelength can be selected so that each FBG sensor has a distinct operational range. This reflected wavelength is called Bragg Wavelength and is dependent on the grating period ($\Delta$) and effective refractive index ($\eta_{eff}$) as given in equation (1). [3]

$$\lambda_b = 2\Delta\eta_{eff} \quad (1)$$

When strain is applied on a FBG sensor, the the grating period changes. This will attribute as a change in the reflected wavelength and is called Bragg shift ($\Delta\lambda_b$). This change can be due to many factors but in this case it constitutes of two components; $\Delta\lambda_{b1}$ which is due to the physical strain applied on the body and $\Delta\lambda_{b2}$ which is due to the thermal strain induced in the fibre due to the change in temperature. These two being independent of each other, can be directly added or subtracted to find the required components of strain.

$$\Delta\lambda_b = \Delta\lambda_{b1} + \Delta\lambda_{b2} \quad (2)$$

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This property of an FBG sensor to measure very large strains (up to 5000 μm/m) [4] with good accuracy has enabled its use in measurement of various physical parameters such as displacement [5], temperature [6], pressure, strain , vibration, acceleration, torsion[7], fluid flow[8] etc. The inherent properties of a FBG sensor and use of optical fibre also deliver various advantages such as remote sensing, passive operation, corrosion resistance, multiplexing capabilities of up to 10 FBG sensors in a single optical fibre by using wavelength division multiplexing (WDM). This sensor is also small in size (250 μm dia), enables measurement of multiple parameters using a single fibre, is impervious to electrical & magnetic interference and can have long distance signal transfer without repeaters.

## 2. Flow measurement using FBG

The above mentioned properties of FBG sensors have attracted many researches in the area of measurement of flow parameters. Some of the major works in this direction are listed below.

Some of the initial concepts of FBG based flow measurement used these sensors as a temperature transducer. The principle of anemometry has been applied for these measurements. In one case, a FBG sensor kept downstream to a heating element which is placed in the path of flow was used to measure the temperature variations [9]. The measured temperature was proportional to the rate of flow, due to higher dissipation of heat due to convection at higher flow rates. In an improvement over this design, a node created around the FBG sensor was heated using laser beams and the temperature difference due to the flow variation was recorded [10]. Both these methods, though feasible included introducing heat into the flow stream, which is not desirable in case of cryogenic fluids.

A different approach that was explored was to use FBG sensors in target type flow meters. In these applications, a target body is placed in the path of flow. The force induced is measured in terms of the strain on the support element. This can be a cantilever rod or a thread running axially. These designs usually present with higher pressure drop across the sensor and can introduce turbulence to the flow. Some low-pressure drop designs were presented using a concentric cylinder type target, in which only drag force due to flow is used in the flow measurement [11].

### 2.1. *Flow meter design*

In the flow meter design being proposed, the concept of using a discrete target body is eliminated [12]. This eliminates difficulties such as unnecessary frictional resistance, pressure drop etc. Instead the FBG fibre is placed directly in the path of flow, such that the fibre is perpendicular to the direction of flow. The schematic for the design is shown in Figure 2.

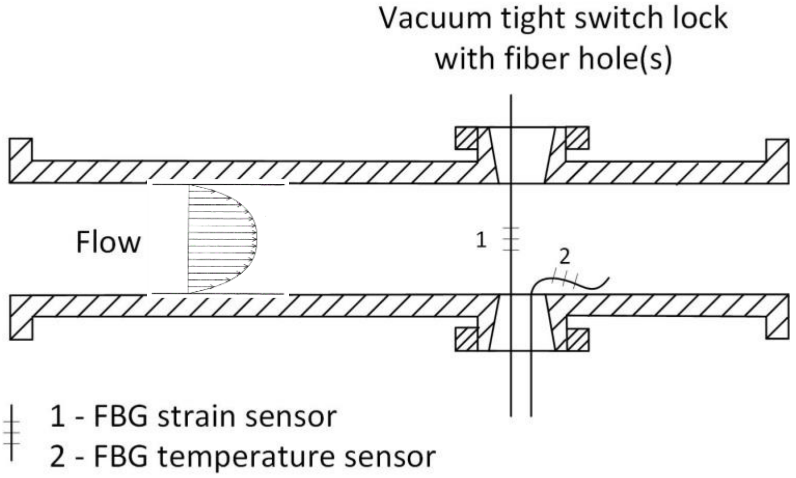


Figure 2 Schematic of the designed flow meter

Developing length for the flow meter is estimated (equation (3)); where D is the diameter of the tube and Re is the Reynolds number and the sensor is placed at the point where a fully developed flow exists. This is important to ensure this, so as to avoid any asymmetric forces affecting the fibre.

$$L_h = 1.359D(\mathrm{Re})^{\frac{1}{4}} \tag{3}$$

The viscous drag created due to the flow will cause a bending force on the on the fibre, which is given by equation (4).

$$F_D = \frac{1}{2} C_D \rho v^2 A_P \tag{4}$$

Where $C_D$ is the drag coefficient, $\rho$ is the fluid density, $v$ is the flow velocity and $A_p$ is the projected area.

The fibre is pre-strained and attached to the pipe walls using Teflon bush and Swagelock™ pipefitting [13]. It is ensured that the FBG sensing part does not come in contact with the pipe walls and is placed exactly at the centre of flow. As the fluid flows across the sensor, its drag force causes a bending strain on the sensor. This induced strain along with any temperature changes cause a Bragg wavelength shift ($\Delta\lambda_b$) in FBG 1.

Another sensor (FBG 2) is placed in the pipe with one end free. This sensor, being un-strained, produces Bragg wavelength shift ($\Delta\lambda_{b2}$) purely due to temperature changes (equation (6)), thus compensating for the thermal effects in FBG 1. Hence, the purely strain dependent Bragg wavelength shift ($\Delta\lambda_{b1}$) of FBG 1 will be the absolute difference between the actual shifts of FBG 1 and FBG 2 as given in equation (2).

$$\Delta\lambda_{b1} = (1-P_e) * \varepsilon * \lambda_b \tag{5}$$

$$\Delta\lambda_{b2} = (\alpha + \xi)\, \Delta T \tag{6}$$

where $P_e$ is strain-optic coefficient, $\varepsilon$ is the strain on grating $\alpha$ and $\xi$ are the thermal expansion coefficient and the thermo-optic coefficient respectively.

### 2.2. Fluid Structure Interaction (FSI) Model

A Fluid Structure Interaction (FSI) model was generated using commercial FEA and CFD codes to check the feasibility of the meter across various mediums and to estimate the operational characteristics of the proposed sensor. The model uses RNG k-ω turbulence model to calculate the drag force acting on the fibre. The data was transferred to a structural solver to calculate the strain over the body. The strain was correlated to the Bragg shift using equation (5) to find the Mass flow – Bragg shift correlation. The properties of fluids for different conditions were obtained from NIST database [14]. The results are discussed in the following section.

## 3. Results

The tests were run using helium gas at 298K for calculating different sensor characteristics such as pressure drop across the flow meter, repeatability, linearity etc. The tests were performed in the flow range of 0-5 $g.s^{-1}$ of gaseous Helium at ambient conditions. It is detected that a zero shift occurs in the FBG sensor due to the pressure of the gas flow. Thus the zero flow condition shifts to a negative value of Bragg shift. During this maximum zero shift recorded is -20 pm, at 0.4 $g.s^{-1}$ for pressure of 20 mbar on an average. The mass flow rate of the fluid was measured using a calibrated differential pressure laminar flow mass flow mater. The schematic of the experimental setup is shown in Figure 3.

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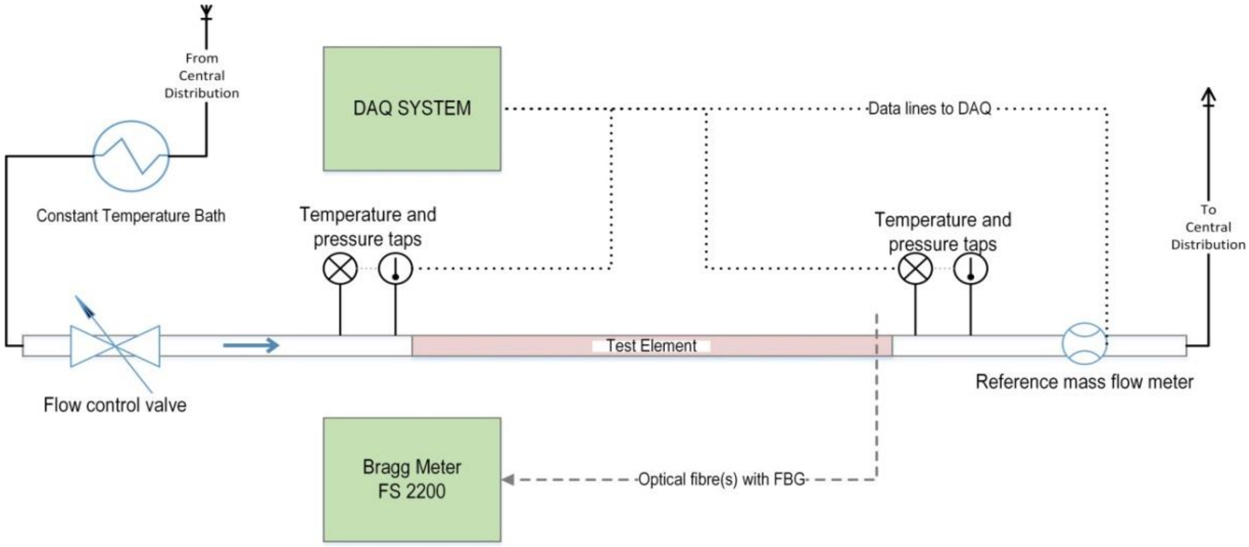



Figure 3 Schematic of the experimental setup used for sensor characterisation

The observations of the experiment are given in Figure 4. It can be seen that the response of the sensor is logarithmic and thus shows a varying sensitivity at various ranges of operation. At flow rates higher that 1.5 $g.s^{-1}$, a near linear operation can be assumed as shown by the sensitivities. At low flow rates of 0-1 $g.s^{-1}$ the sensitivity is low at 9 $pm.(g.s^{-1})^{-1}$ while at higher flow rates, an average sensitivity of 37 $pm.(g.s^{-1})^{-1}$ can be observed.

During a loading-unloading cycle of the flow meter from 0-5 $g.s^{-1}$, it was seen that a maximum variation of 8 pm occurs due to hysteresis. The maximum value of hysteresis was observed at ~2 $g.s^{-1}$ and the deviation is negligible at higher flow rates. This translates to a maximum error of ~0.2 $g.s^{-1}$ during measurement. It should be further seen whether this decreases after a few cycles of operation.

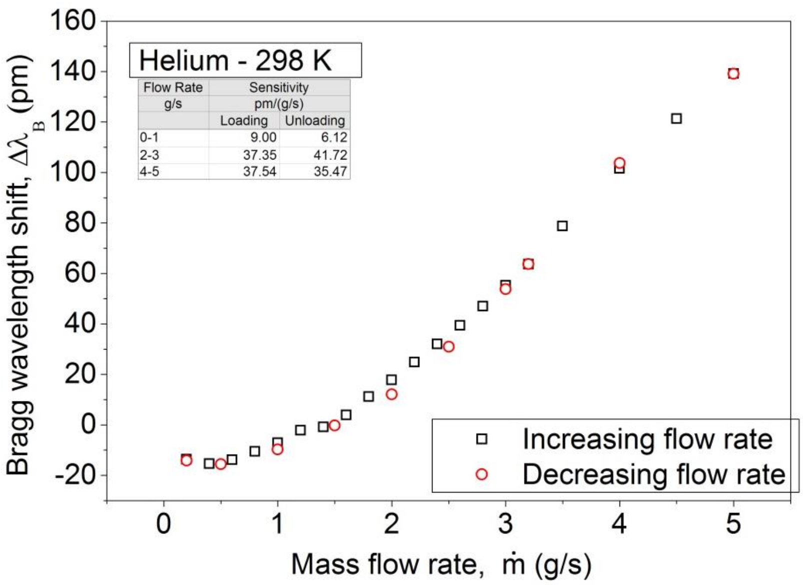



Figure 4 Hysteresis Characteristics of the Flow meter for 0-5 $g.s^{-1}$

The observed data was used to produce a calibration equation relating mass flow rate and Bragg shift. A third degree polynomial was used as the fitting equation. It is seen that the equation provides a very accurate fit over the observed data. The regression curve is shown in Figure 5.

$$y = -12.83 - 8.78x + 14.70x^2 - 1.36x^3 \quad (7)$$

The maximum error during fit was 5%, at the range of 0-1 $g.s^{-1}$ which is in an acceptable range. This accounted for an error of 0.30 pm or 0.008 $g.s^{-1}$. From the error bars, it can be seen that significant fitting errors occur only at one or two points, which may be accounted to dynamic errors during measurement.

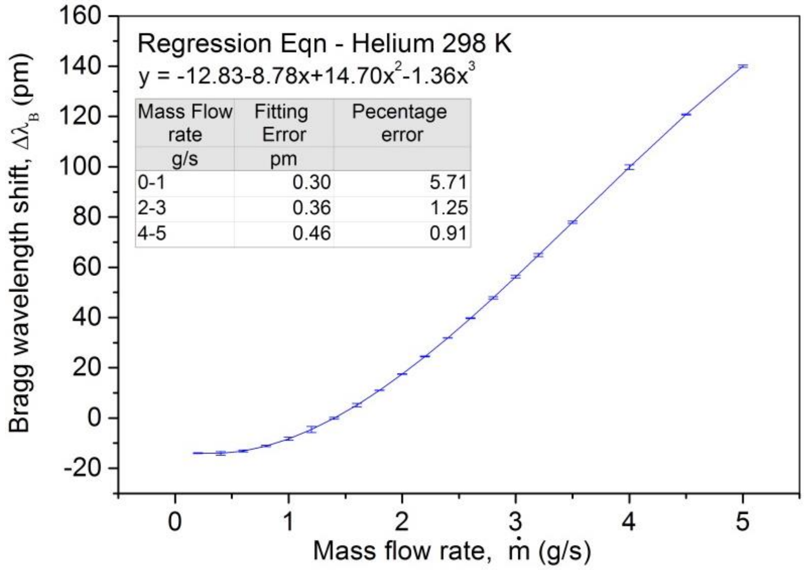
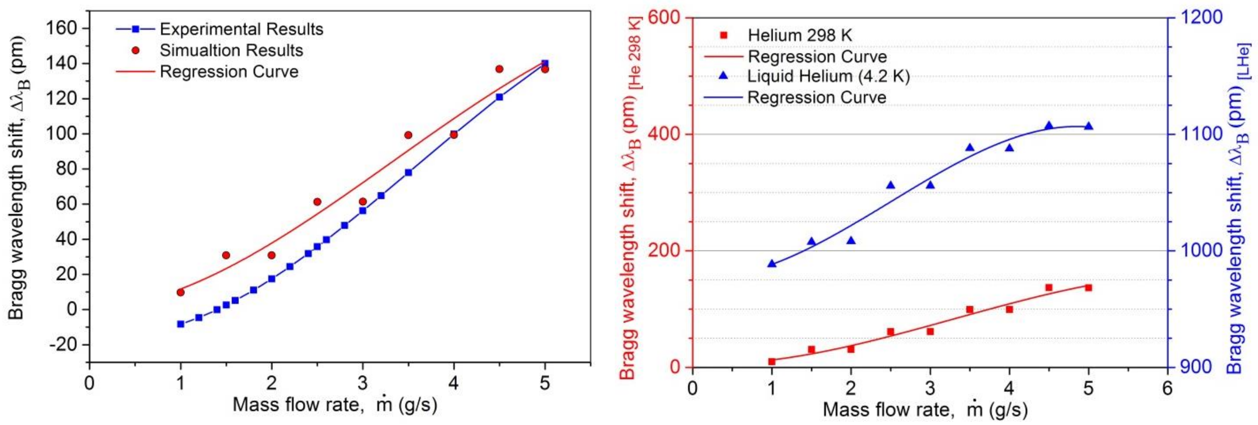



Figure 5 Regression Curve for observed data showing fitting error

To obtain a complete picture of the operational ranges of the sensor a fluid structural interaction (FSI) numerical model was setup. The results were compared to the experimental results and were found to be in agreement (Figure 6 (a)). The model was used to predict the results for liquid helium at 4.2 K and the same is plotted in Figure 6 (b). The results show that the sensitivity of the meter over the whole range is ~35.5 pm.$(g.s^{-1})^{-1}$ for liquid helium, but the initial shift in Bragg wavelength is much more higher, which can result is less environmental errors during measurement.




(a) (b)

Figure 6 (a) Comparison of experimental results with simulation results. (b) Sensor performance data produced from simulations for helium at 298 K and liquid helium (4.2 K)

## 4. Feasibility of the flow meter for cryogens

An important topic of discussion is the feasibility of using the flow meter for cryogenic fluids. FBG sensors have been successfully used in previous situations to measure parameters such as displacement in applications such as superconducting magnets and have been proven to be operating at cryogenic temperatures [6]. Many standard flow meters tend to lose resolution in reading at lower temperature due to effects caused by the temperature difference. In this design a FBG temperature sensor is built-in to the system and will automatically compensate for any variations in output due to temperature changes (Figure 2). Since the flow meter design is a minimal flow resistance design, the flow measurement depends entirely on the fluid properties such as velocity, density and viscosity. It can be seen from the simulation results, that the range of operation for the specific design covers both gaseous and liquid helium, though further design modifications may be done to obtain higher sensitivity or to measure higher mass flow rates as per different area o application.

## 5. Conclusion

Based on the innovative concept of using FBG fibres for measurement of flow parameters by utilizing the drag force on the fibre placed in flow regime, two different designs were produced. The single fibre design was tested using helium gas at 298 K and a good response was observed in the flow range of 1.5-5 $g.s^{-1}$. A sensitivity of 37 $pm.(g.s^{-1})^{-1}$ was observed with a maximum hysteresis error of 0.2 $g.s^{-1}$ during a loading-unloading cycle. A $3^{rd}$ degree polynomial fit was used to produce a calibration equation which showed an average error during fit as 2%. A numerical model was also generated to check the feasibility and to estimate the operational characteristics of the proposed sensor. The model shows same range of sensitivity for liquid helium, but exhibits a higher initial Bragg shift.

A multiple sensor flow meter is also being proposed which can take advantage of various advantages of FBG sensors such as multiplexing, interference free operation etc. to perform measurements such as mass flow measurements in two phase flow, turbulence parameters, velocity mapping of flow cross section etc. The principle of operation for the new meter is same as that of single fibre model. The concept behind this design is to establish an array of sensors across the flow cross section, to measure flow properties at multiple points in the flow domain.

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