Improving Simulation Accuracy of a Downsized Turbocharged SI Engine by Developing a Predictive Combustion Model in 1D Simulation Software

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Abstract

In this paper we aim to develop a predictive combustion model for a turbocharged engine in GT-Power software to better simulate engine characteristics and study its behavior under variety of conditions. Experimental data from combustion was initially being used for modelling combustion in software and these data were used for model calibration and result validation. EF7-TC engine was chosen for this research which is the first turbocharged engine designed and developed by IKCO and IPCO in Iran. After analyzing necessary theories for predictive combustion model and required steps for calibration of CombSITurb model in software, one final set of multipliers were calculated based on different sets derived for each engine speed and engine operation was simulated with this combustion model. In addition to improved predictability of engine model, comparing results of predictive model with non-predictive model shows better accuracy especially at lower engine speeds and less tolerance of results for each engine speed.

Keywords: *Turbocharged engine; GT-Power; 1D Simulation; Combustion Model; Predictive*

1. Introduction

With dawn of 21st century and better development of commercial 1D engine simulation softwares like Gamma Technologies GT-Power, number of papers in the category of 1D engine simulation have increased as well. Despite inherent inaccuracies of 1D models compared to 3D ones, this method is still preferred over 3D simulation for its less computational time in first steps of research and developments in automotive industry. Difficulties in simulating turbulent affected phenomena like combustion, heat transfer and turbocharger flow in 1D simulation codes have made researchers to develop new approaches to better model these engines in 1D simulation softwares.

Since combustion is always considered as one of the main areas in engine modelling and simulation, many researchers have focused on developing better and more accurate models for simulating combustion in IC engines. In 2007, Bozza et al. studied steady state and transient simulation of a downsized charged engine. The key part of their model is a novel combustion model based on fractal nature of the turbulent flame. This model covers different phases for combustion including flame initiation, laminar burning and turbulent burning. Heat release rate is computed in this two-zone model which includes a turbulent sub-model. This turbulent sub-model was tuned using 2D data gathered from CFD computations. Laminar flame surface was calculated through a CAD procedure as well. A 3D representation of combustion chamber was imported in CAD software which predicts all possible positions of the flame at every crank angle [1]. Later that year, Bozza et al. utilized this fractal combustion method in another model with a 3D CFD approach for cylinder in-flow and turbulent indices. Numerical results were in good agreement with experimental data and it was concluded that coupling models of different hierarchical level can be a useful tool [2]. This method was used again in another research from this team in 2014 for enhancing predictability of combustion model [3].

Predictability of combustion model is one of the most important factors in engine simulation. In most 1D simulation models, non-predictive combustion models like Wiebe functions are used which are derived from experimental data from combustion. Using these models one is unable to simulate engine in conditions other than that in combustion experiments. Therefore, developing predictive combustion models is of paramount importance when dealing with engine simulation, characteristic analysis and optimization. Examples of these kind of researches can be found in [4], [5], [6] and [7]. These authors have developed different predictive models to better simulate combustion in IC engines using 1D simulation codes. Improving predictability of combustion is not limited to gasoline or diesel cars only and there has been researches into modeling combustion for hybrid powertrain simulations as well. Example of these literature can be found in [8].

Limited access to combustion experimental data has led many researchers to use non-predictive models in Iran. In this paper, we use several experimental combustion data for different engine speeds to develop a predictive combustion model for EF7TC engine model in GT-Power simulation software. Engine model is then validated with experimental data utilizing this predictive combustion model.

2. Engine data and basic simulation results

EF7-TC is turbocharged variant of EF engine family produced by IKCO. This engine is considered to be bi-fuel but in this paper gasoline-only mode has been chosen. Main specifications and performance limitations of EF7-TC is shown in **Error! Reference source not found.**.

GT-Power was chosen for modeling and simulation of engine for its versatility and extensive library for different component of IC engines. Schematics for engine model is shown in **Error! Reference source not found.**. Manifold inlet, compressor outlet, intake and exhaust valves, turbine inlet and exhaust pipe has been modeled using data gathered from IPCO and IKCO. The engine was modeled using experimental data for ignition timing and lambda acquired from IPCO for different engine speeds and loads. Experimental data for combustion heat release rate profiles was initially implemented in model to simulate combustion in different speeds.

Utilizing this non-predictive combustion model leads to good correlation of IMEP and brake torque for this basic engine model. Results for IMEP and brake torque are shown in **Error! Reference source not found.**. The overshoot for 2000 rpm in both figures can be result of turbocharger dynamics since turbocharger efficiency sub-models hasn't been calibrated at all. Moreover, Inaccuracies linked with turbocharger efficiency sub-models will have impact on turbocharger related parameters like manifold air pressure, compressor outlet pressure and turbine speed but they're not considered in this paper at all.

Table 1: EF7TC Engine Specifications

Description	Value	Unit
Displacement	1.649	L
Compression ratio	9.5	-
No. of Cylinders	4	-
Bore x Stroke	78.6 x 85	mm
Connecting rod	134.5	mm
Max. torque	215@2200-4500 rpm	N.m
Max. power	110@5500 rpm	kW
Max. turbocharger Speed	220000	rpm
Max. pre turbine temperature	930	°C
Minimum Lambda	0.75	-
Fuel research octane number	95	-
Fuel low heat value	42.76	MJ/kg

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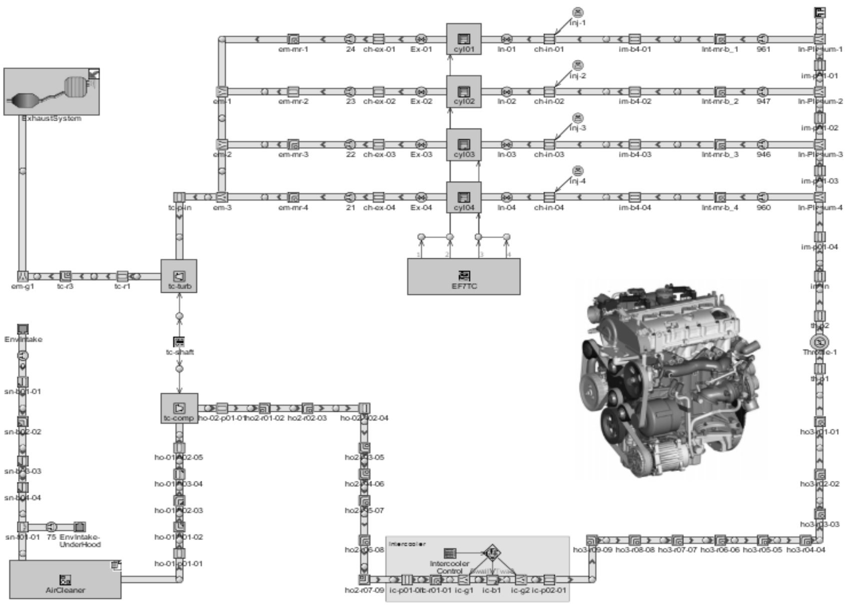

Fig1. Schematics of model map in GT-Power Software

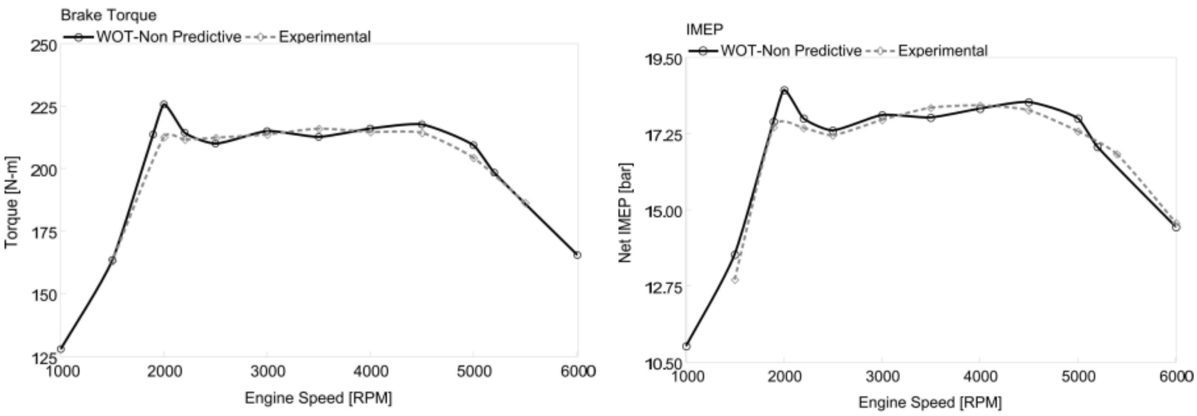

Fig2. Brake Torque (Left) and IMEP (Right) for base model with non-predictive combustion model

3. Predictive model theory

Predictive combustion model in GT-Power is based on combustion theory of laminar and turbulent flame speed. Net heat release rate at every crank angle is then calculated using these theories and amount of unburned mixture engulfed in flame front.

4. Laminar flame speed

The following equation is used in GT-Power software to calculate laminar flame speed at every crank angle of simulation. Basic fundamentals of this equation is described here but more in-depth analysis can be found in [9].

$$S_L = (B_m + B_\phi(\phi - \phi_m)^2)(\frac{T_u}{T_{ref}})^\alpha(\frac{p}{p_{ref}})^\beta(1 - 2.06(Dilution)^{DEM-0.77})$$

B_m is maximum laminar burning speed and is calculated based on different fuel mixtures. Metghalchi and Keck experimented on this subject and obtained this parameter for different fuel mixtures. Results of their work can be seen in

ϕ_m is equivalence ratio at which maximum laminar burning speed occurs. This parameter is derived from

Error! Reference source not found. as well and for most fuel mixtures is little bit over 1 and stoichmetric ratio. The first part of equation 1 shows amount of deviation from maximum laminar burning speed for a given mixture equivalence ratio and is called $S_{L,O}$ in other literatures like [9].

The second part of equation 1 is for calculating effects of temperature and pressure on burning speed. T_u is temperature of unburned zone and p is cylinder pressure in this equation. Reference values for temperature and pressure in denominator of each divisions are 298 kelvin and 101325 pascal, respectively. Division exponents α and β are calculated from following equations to count for effect of mixture equivalence ratio on temperature and pressure [12].

$$\alpha = 2.4 - 0.271\phi^{3.51}$$

$$\beta = -0.357 + 0.14\phi^{2.77}$$

The third and last part of equation 1 is for calculating effect of dilutants on laminar burning speed. Dilutants can be EGR gasses or residuals from last cycle or anything that dilutes mixture in cylinder and since these dilutants are very hard to quantify, there is a multiplier built into this part of software to calibrate results of simulation with experimental data. This multiplier is called Dilution Exponent Multiplier or DEM and is one of the 4 multipliers of ComSITurb combustion model that needs to calibrate.

5. Turbulent flame speed

In GT-Power, turbulent flame speed is calculated based on flame front movement theory. In other words, amount of unburned mixture mass entertained into the flame front as it moves forward is calculated by combustion model. Schematics of this assumption is shown in along with parameters that are used in modelling this phenomenon. The flame front moves outward at laminar flame speed S_L and unburned mixture is entertained into the flame at characteristic velocity u_T due to turbulent convection [9].

The following equations is used for modelling combustion in "entertainment" or "eddy-burning" model. Reason for this name is that equation (4) represents laminar or diffusive propagation of turbulent flame while second term of this equation calculates burning of already entertained mixture within this flame front. Equation (5) describes rate of change of unburned mixture mass within the flame front which is shown with parameter μ. In fact, the first term of this equation represents the turbulent convection of unburned mixture across the flame front and second term represents the mass rate of entertained mixture. This mass is contained within the wrinkles and islands shown in left side of **Error! Reference source not found.** and is characterized by a characteristic length in form of l_T. The relation of this characteristic length with combustion is evident from equation (6). Equation (7) is used for calculating characteristic burning time. By definition, this equals the time required for laminar flame to develop into turbulent flame [9]. More details of these equations and turbulent combustion model can be found in [13], [14] and [15].

$$\frac{dm_b}{dt} = \rho_u A_f S_L + \frac{\mu}{\tau_b}$$

$$\frac{d\mu}{dt} = \rho_u A_f u_T (1 - e^{-t/\tau_b}) - \frac{\mu}{\tau_b}$$

$$\mu = m_e - m_b = \rho_u (V_f - V_b) = \rho_u l_T (A_L - A_f)$$

$$\tau_b = \frac{l_T}{S_L}$$

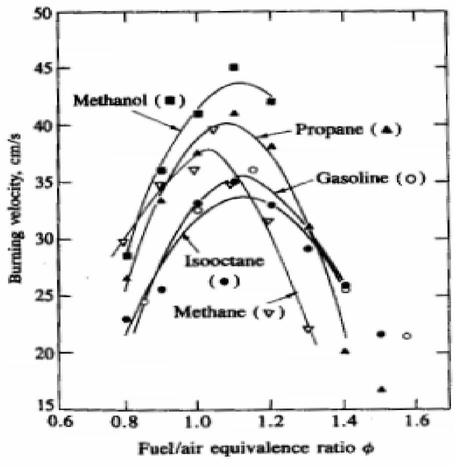

Fig3. Maximum laminar burning speed for different fuel mixtures [10], [11]

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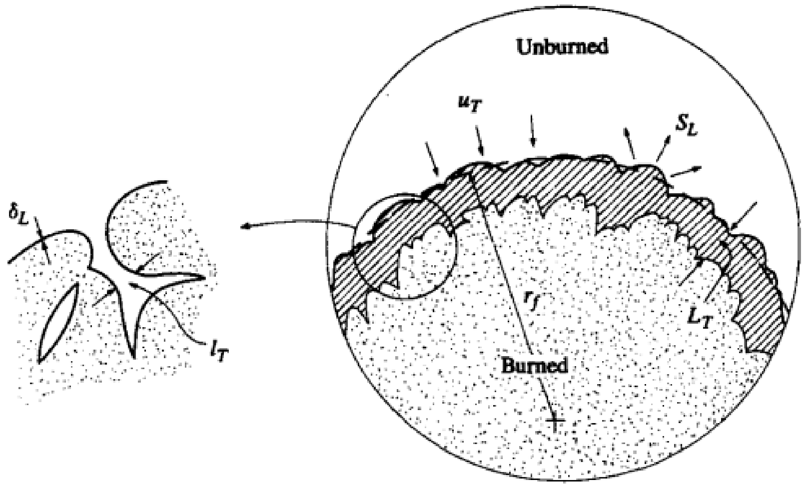


Fig4.:Schematic of turbulent premixed SI engine flame [9]

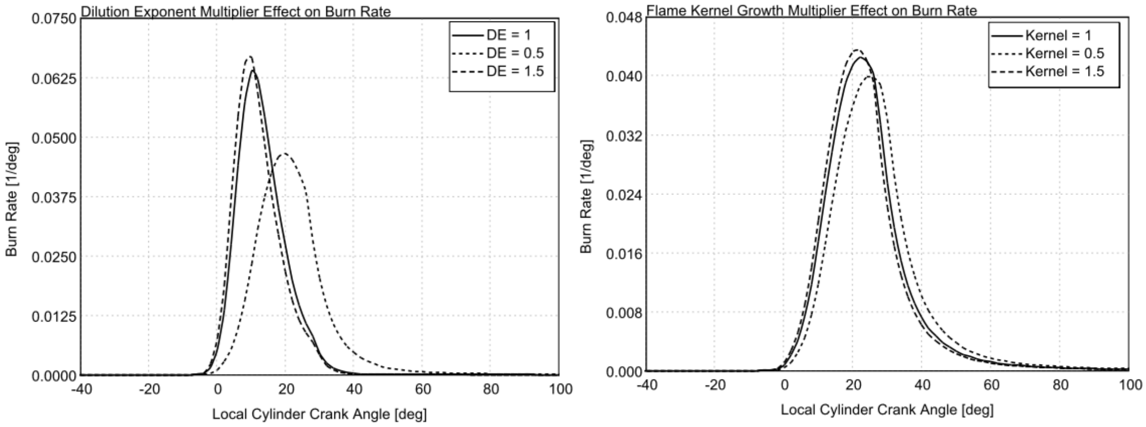


Fig5.: Effect of Dilution Exponent Multiplier (left) and flame kernel growth multiplier (right) on burn rate

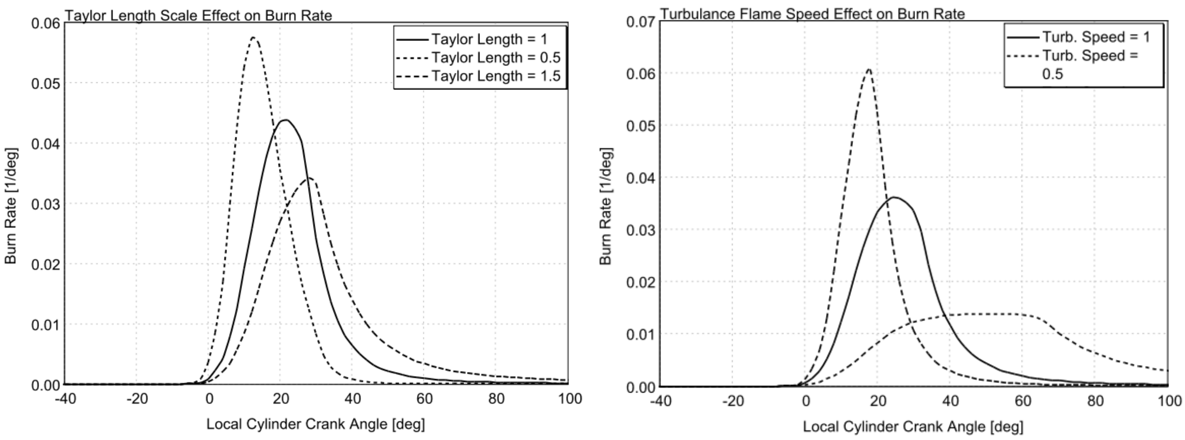


Fig6. Effect of Taylor Length Scale Multiplier (Left) and Turbulence Speed Multiplier (right) on burn rate

6. Model calibration

There are different ways for calibrating a predictive combustion model in GT-Power simulation software which must be utilized based on experimental data in hand. DoE methods might look most promising with large sets of data and so have been used for calibration of this predictive model in the past. Example of this calibration can be found in [16]. Another different method of calibration for ComSITurb model in GT-Power is done by matching simulated results with experimental one. This method is largely used by previous researchers and examples of their work can be found in [4] and [17]. Due to less computational resource requirements, the latter method was chosen for this paper.

7. Parameter analysis

As it was stated before, there are 4 multipliers in CombSITurb model which has to calibrated in order for predictive combustion model to have accurate results. Complex interaction of these 4 multipliers on combustion mechanism led authors to analyze each multiplier alone before correlating simulation with experimental data.

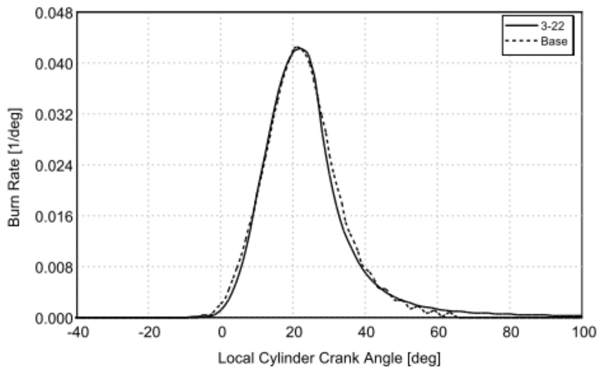
Error! Reference source not found. shows the effect of dilution exponent multiplier or DEM on burn rate. As it is mentioned in [9] and [14], start of combustion and flame initial propagation is mostly influenced by dilutants which is evident from **Error! Reference source not found.**. According to equation (1), increasing DEM results in more dilutants in equation which slows the combustion and reduces maximum burn rate. Decreasing DEM however, increases the flame initiation and maximum burn rate. Burn rate profile is greatly sensitive to this multiplier. Effect of flame kernel growth multiplier is shown in this figure as well. This multiplier directly impacts flame propagation and is relatively insensitive to burn rate.

Effect of last two multipliers on burn rate is shown in **Error! Reference source not found.**. These two multipliers mostly affect turbulent flame speed and directly related to it. Taylor length scale multiplier influences the time needed for laminar flame to develop into turbulent flame and increasing it will make combustion faster which will move maximum burn rate forward in lower crank angles. Same analogy can be said for turbulent flame speed and increasing this multiplier will accelerate burn rate as well. These phenomenon is evident from burn rate profiles in **Error! Reference source not found.**.

8. Burn rate correlation

Based on findings of section 4-1, simulation results of burn rate is compared with experimental burn rate for 9 different engine speeds. It must be said that because of lack of sufficient data from EGR and residuals from last cycle, this correlation cannot be done with consistent accuracy and correlation accuracy level will be different for each engine speeds. An example of accurate correlation can be seen in **Error! Reference source not found.** in which simulated and experimental burn rate profiles for 5000 rpm have matched each other but same level of accuracy cannot be seen for 2200 rpm.

It was decided to use an average model for all engine speed as a result of this inconsistency. Therefore, an average of each multiplier for all 9 engine speeds were calculated and this average set was used as input for predictive combustion model. Result of engine simulation with this predictive model showed good level of accuracy for whole operating range of engine from 1500 rpm to 5500 rpm. Results of simulated operating parameters is shown in **Error! Reference source not found.**.



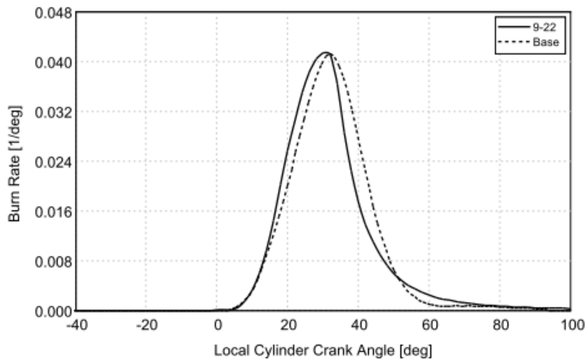


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Fig7. Simulated and experimental burn rate for 5000 rpm (Left) and 220 rpm (Right)

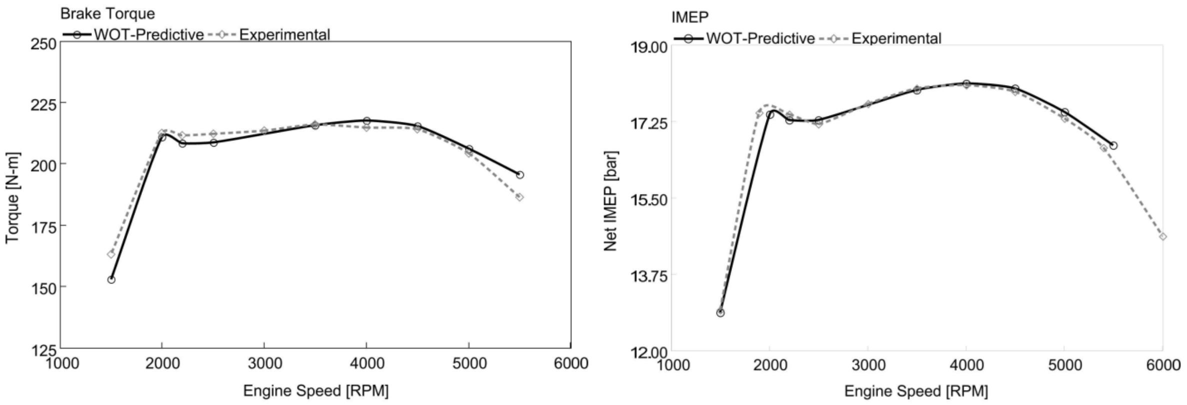

Fig8. Brake Torque (Left) and IMEP (Right) for model with predictive combustion model

9. Conclusion

Analysis of different multipliers of predictive combustion model helped authors to gain extensive knowledge of each multiplier and its effect on simulated burn rate. Using this knowledge, proper set of multipliers were chosen for each engine speed with good correlation with experimental burn rates. Ultimately, only one set of numbers was calculated from all engine speed to hold good accuracy across whole operating range of engine.

In addition to improved predictability of engine model, comparing results of **Error! Reference source not found.** with **Error! Reference source not found.** shows better accuracy especially at lower engine speeds and less tolerance of results for each engine speed. Moreover, this model is now capable of simulating engine characteristic under different engine conditions which is useful for transient simulation and engine development reasons.

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