THERMAL CHARACTERIZATION OF INSULATING MATERIALS

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ABSTRACT

With the improvement of the standard of living, the building's energy consumption is likely to increase. Consequently, government agencies have to improve the efficiency of their buildings' energy use. A reduction of the latter can save money, and reduce greenhouse gas emissions, since most of this energy is of fossil origins. The use of thermal insulation is one of the most important passive energy conservation measures in buildings. Knowledge of thermal properties is essential for the selection of existing materials and the development of new insulating materials. The focus of the present paper is to determine the thermal diffusivity of 5 insulating materials, which are commercially available, being used or to be introduced to the Tunisian market. The thermal diffusivity for building material was experimentally predicted using a newly apparatus and analytical model. The results were compared with a numerical model.

1. INTRODUCTION

In Tunisia, the building energy consumption is likely to increase with the improvement of the standard of living. The energy consumption in the building sector exceeds the third of the total energy consumption in all sectors. A reduction of the latter not only saves money, but significantly reduces greenhouse gas emissions, since most of this energy is of fossil origins. The government aims to reduce their energy consumption through an architectural approach adapted to Tunisian climate. The use of thermal insulation is one of the most important passive energy conservation measures in buildings. Insulation is mainly used for thermal purposes. Knowledge of thermal properties such as the thermal diffusivity is essential for the selection of insulating materials. Thermal diffusivity is an important material property in all applications involving time-dependent heat conduction as it is related to the propagation velocity of heat in the considered medium.

The determination of the thermal diffusivity of insulating materials has been developed for many decades.

There exist several methods for the direct measurement of the thermal diffusivity of insulating materials. All of them use the temperature time-response at a fixed point in the sample that has one of its faces subjected to a time-dependent temperature or heat flux condition. The flash method is one of the techniques which have been employed for determining the thermal diffusivity of solids by numerous workers e.g. Parker [1], Hay [2], Vozar [3], and Degiovanni [4].

Measuring or estimating thermal properties of anisotropic building materials is proposed by B.Yesilata and P.Turgut [6]. The measurement is based on analysis of transient data, which is suitable for comparing effective thermal transmittances of both isotropic and anisotropic building materials. The experimental study properties of condense formation, drainage and moisture dependent heat transmittance were studied for three different thermal insulation materials by F. Björk and T. Enochsson [7]. Y. Gao and al [8] have evaluated the thermal diffusivity and the effusivity of a granular material. The global and local characterization of the thermal diffusivities of SiCf/SiC Composites with infrared thermography and flash method is developed by M. Bamford and al [9]. A. Prociak and al [10] have evaluated thermal diffusivity of rigid polyurethane foams blown with different hydrocarbons. J.-L. Vivancos and al [11] proposed an experimental model to characterize the material.

All of these works used an analytical model to evaluate thermo-Physical properties of building insulating materials.

The present study is performed within the framework of the program of thermal and energy regulation of new buildings in Tunisia. This paper describes a new apparatus for measuring the thermal diffusivity under stationary conditions and using an analytical model. The results were compared with numerical model.

2. METHODOLOGY

2.1. Description of the experimental apparatus

The apparatus shown in figure 1 consists of a plexiglas box has a dimension of 0.50 × 0.30 x0.30 m^3 with a mobile cover. It is highly insulated thanks to a thick layer of expanded polystyrene in order to reduce the eventual heat loss between the outer plate and the ambient. It contains a heat exchanger circulating a hot water thanks to a pump with an electric heater. This heat exchange allows the measurement of the thermal diffusivity of the sample placed respectively between heat exchange and the insulating material. The samples have to have a square section of 27 cm sides and a variable thicknesses. Heat exchanger formed by a copper box has a dimension of 0.27 × 0.27 m^2.

The temperatures are measured with platinum probes. Each sample is provided with two surface probes, fixed on the respective faces . All temperature sensors are connected to an AGILENT 34970A data acquisition system allowing the acquisition and the storage of the temperature signals on a person computer with an accuracy of 0.1 °C.

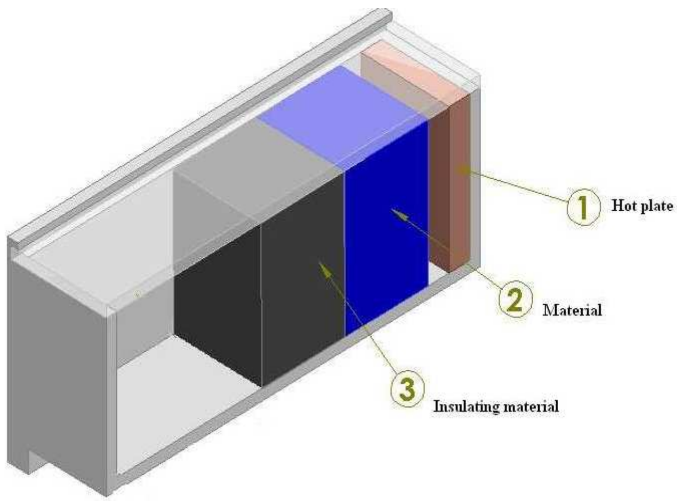

Figure 1. Experimental apparatus

2.2. Procedures

The principle of this method can be described as follows. The sample receives a thermal impulse. The resulting heat flux crosses the sample from the irradiated face towards the opposite face to the impulse is adiabatic. Thermocouples fixed in the middle of the sample faces and connected to a computer data acquisition card yield temperature thermograms (time-series) for the respective faces of the sample. These thermograms can be used to calculate the thermal diffusivity.

3. Mathematical formulation

In this study the sample have to have section of 27 cm sides and thickness of 4 cm. The sample, initially maintained at temperature T_i, heated by a constant temperature T_0 the opposite to the excitation face is isolated by the rock wool Figure2.

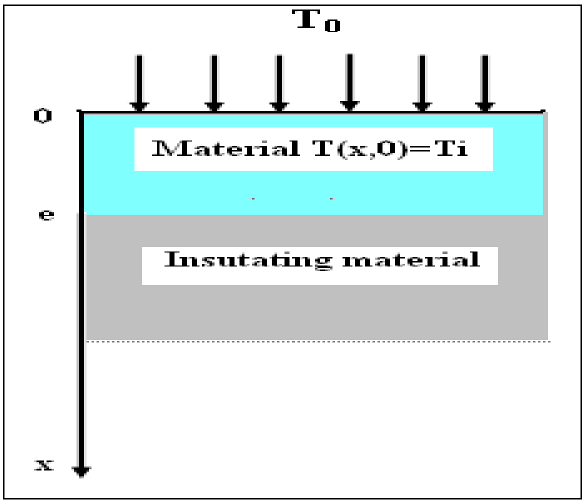

Figure 2. Experimental model scheme

For temperature independent material thermal properties, the one-dimensional unsteady conduction is represented by the Fourier equation:

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad (1)$$

The solution of the Fourier Equation (1) along with the recorded thermograms can be used to calculate the thermal diffusivity. Several interpretation techniques of the thermograms exist in the literature, among which those of Parker [1] and the partial time moments technique introduced by Degiovanni [4-5]. In all of these interpretation techniques, it is necessary to satisfy the following conditions:

- The one-dimensional unsteady conduction
- The incident energy of the impulse must be distributed uniformly on the excited face.
- The studied medium could be considered homogeneous.
- Absence of the source of internal warmth

To solve equation (1) it is necessary to know the initial and the boundary conditions. Initially the temperature is uniform in all the medium

$$T(x,0) = T_i \qquad (1\text{-a})$$

The boundary conditions are given as:

- The interior side was heated at the temperature

$$T(0,t) = T_0 \qquad (1\text{-b})$$

- The exterior side was isolated by the wool of rock outside we can write

$$-\lambda \frac{\partial T(e,t)}{\partial x} = h(T - T_i) \qquad (2)$$

Where, λ is the thermal conductivity, h is the convective coefficient exchange and T_i the initial face temperature.

3.1 Analytical model

Equation (1) can also be solved by the separation of variable method when the convective coefficient exchange was assumed h=0. The solution may be obtained by introducing a new variable θ satisfied by $\theta = T(x,t) - T_0$

The final solution of the temperature is expressed as:

$$T(x,t) = T_0 + (T_i - T_0)\frac{4}{\pi}\sin\left(\frac{\pi}{2e}x\right)\exp\left(-\alpha t\left(\frac{\pi}{2e}\right)^2\right) \qquad (3)$$

Where λ the thermal diffusivity, e is is the sample thickness, T_i and T_0 are respectively the initial and exterior face temperature.

The temperature of the opposite face can be expressed as :

$$T(e,t) = T_0 + (T_i - T_0)\frac{4}{\pi}\exp\left(-\alpha t\left(\frac{\pi}{2e}\right)^2\right) \qquad (4)$$

When the temperature reached half of its maximum value at the opposite to the excitation face, we determine $t_{1/2}$ the half-rise time i.e. the time interval, relative to the pulse. Thus the thermal diffusivity is determined as

$$\alpha = -\frac{1}{t_{\frac{1}{2}}}\left(\frac{2e}{\pi}\right)^2 \mathrm{Ln}\left(\frac{4}{\pi}\left(1 - \frac{1}{2}\left(\frac{T_\infty - T_0}{T_i - T_0}\right)\right)\right) \qquad (5)$$

Knowing the sample thickness used and the time $t_{1/2}$ obtained for the experimental curve of the reduced versus time, it is possible to determine the value of the later propriety.

3.2. Numerical method

The dimensional governing Eq. (1) along with the boundary conditions given by Eqs. (1-a) –(1-b) and Eq.(2) were discretized by the classical finite volume method Patankar [13].The calculated domain is discretized by a unidirectional uniform grid of *n* control volumes of dimension *Δx* . In order to ensure stability, a fully implicit scheme is used for the temporal derivative. After initializing all the variables (i.e., the interior and exterior wall sides and the medium temperatures), and choosing arbitrary values of these variables (see Figure 3). The numerical iterations were advanced in time until:

$$\max\left|\frac{T_n^{i+1} - T_n^i}{T_n^i}\right| < 10^{-4}$$

Where T stands for position (n), and i is the iteration level.

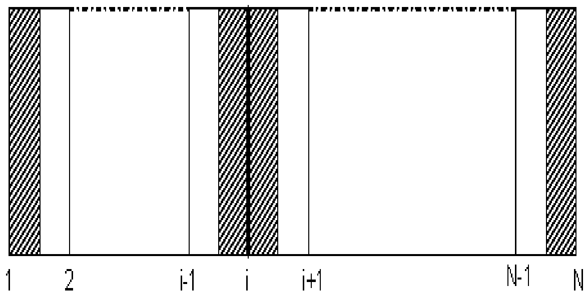

Figure 3. Numerical grid

The numerical simulation allowed us to determine the spatio-temporal evolution of the temperature and the average temperature calculations are obtained for the insulating material.

4. RESULTS AND DISCUSSION

In this paper we are interested in the study of the effect of thermal diffusivity and the convective coefficient exchange h on heat transfer for different materials. The numerical simulation has been performed for square samples which have section of 27 cm sides and thickness of 4 cm.

In steady one-dimensional conditions, one can determine the thermal diffusivity by measuring the heat flux through the sample and the temperature difference between its two faces. In order to insure steady state conditions, the heat exchanger is provided with five surface probes (platinum probes) fixed on various place (see Figure 4).

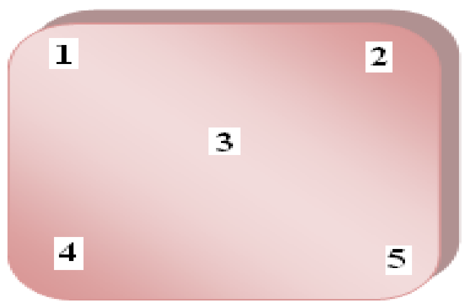

Figure 4. Location of the probes on the face of the heat exchanger

Figure 5 shows that the measurements were carried out after at least 30 min from setting the experimental conditions.

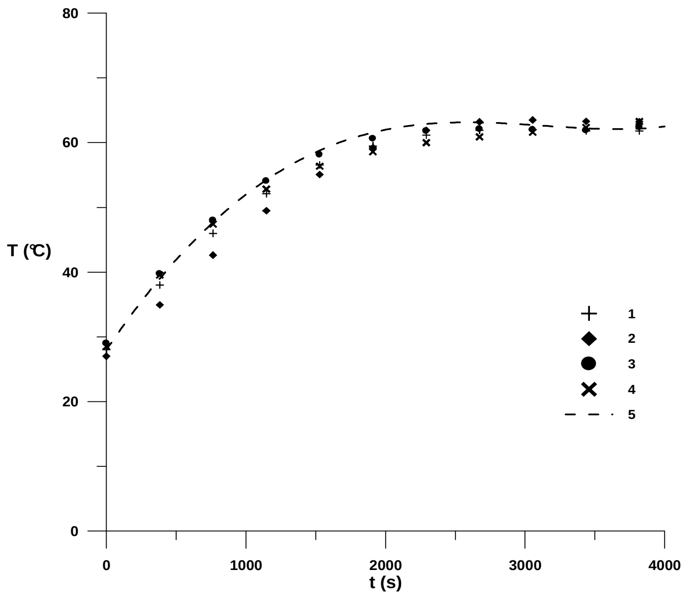

Figure 5. Variation of temperature with time

4.1. The effect of the thermal diffusivity

In order to study the effect of the thermal diffusivity on establishing of the steady state regime, we have fixed the value of the convective coefficient exchange at h = 4W/m^{2}K, using the numerical simulations, with different values of thermal diffusivity (10^{-5}, 10^{-6}, 10^{-7}) m²/s, the temperature of the opposite impulse face according to time variation curve are plotted in Figure 6. We can see that decreasing the thermal diffusivity leads to increase of the establishing of the steady-state regime.

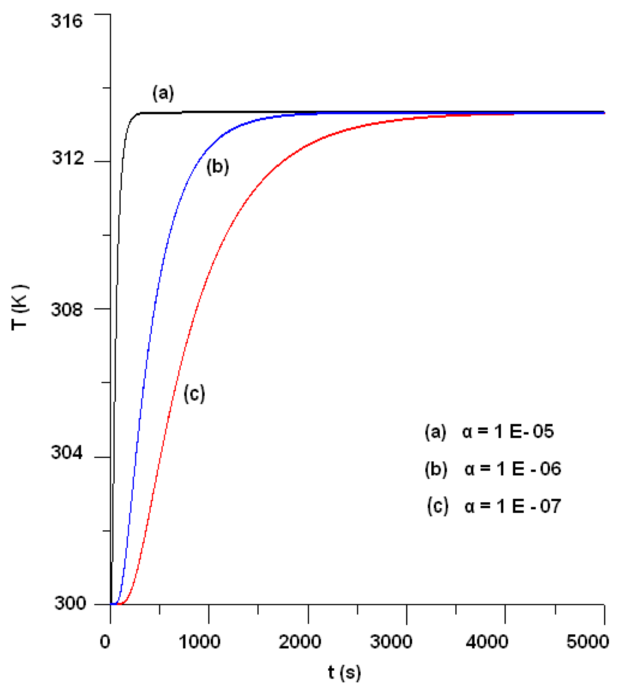

Figure 6. The temperature of the opposite impulse face according to time variation curve

The steady-state establishing time according to the thermal diffusivity variation curve plotted in figure 7. We can see that this increase becomes very quick for values which do not exceed 10^{-5} m²/s.

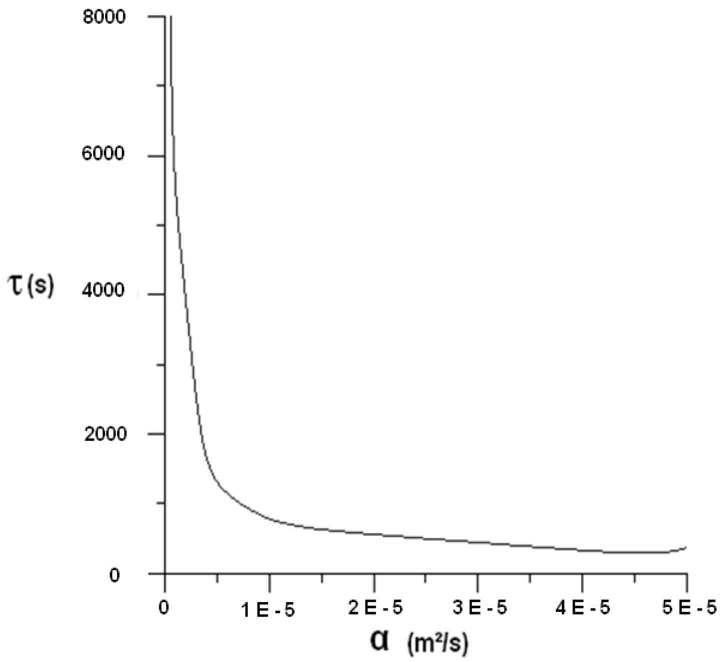

Figure 7. The steady-state establishing time according to the thermal diffusivity variation curve

4.2. The effect of the heat transfer coefficient

In order to study the effect of the convective coefficient exchange on establishing of the steady state regime, we have fixed the value of thermal diffusivity at 10^{-7} m²/s, the temperature of the opposite impulse face according to time variation curve are plotted in figure 8.

We notice that increasing of the convective coefficient exchange leads to decrease of the establishing of the steady-state regime. This effect becomes negligible for values superior of 4W/m^{2}K.
The steady-state establishing time according to the convective coefficient exchange variation curve plotted in figure 9. We can see that h has an effect also on the temperature of the opposite impulse face attained on the steady-state regime, by increasing the convective coefficient exchange, the temperature decrease.

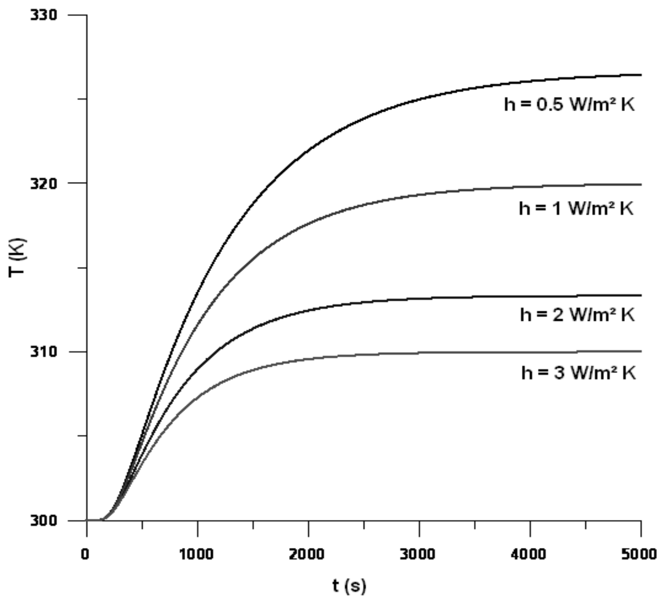

Figure 8. The temperature of the opposite impulse face according to time variation curve

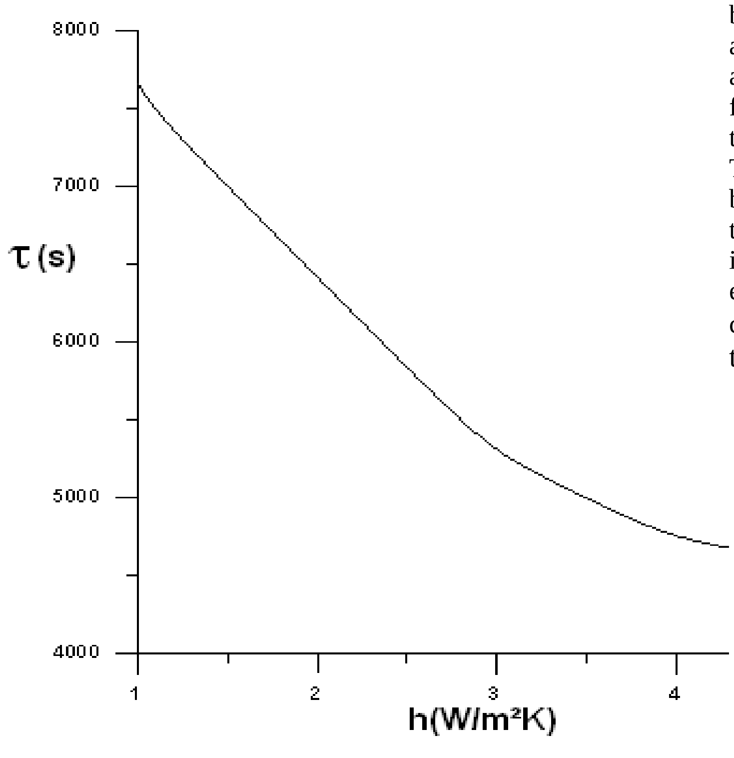

Figure 9. The steady-state establishing time according to the coefficient convective exchange variation curve

4.3. Determination of the thermal diffusivity

It is widely agreed upon that thermal diffusivity informs us about the propagation velocity of heat in the medium considered. When the value of diffusivity decreases the heat transfer trough the considered medium becomes difficult. In thermal engineering processes, the knowledge of this thermal property is of great importance because it informs us about the nature of materials.

For this reason we have realized a new apparatus for measuring the thermal diffusivity under stationary conditions of thermal insulators [12].

The sample receives a thermal impulse. The resulting heat flux crosses the sample from the irradiated face towards the opposite face to the impulse is adiabatic. Temperature sensors fixed in the middle of the sample faces are connected to an AGILENT 34970A data acquisition system allowing the acquisition and the storage of the temperature signals on a personnel computer. These thermograms can be used to calculate the thermal diffusivity. We can use the quadratic error medium between calculated and measured temperatures we search domain of α and h.

We have compared the numerical model to the experimental data. The numerical and experimental values of the thermal diffusivity and the convective coefficient exchange for the commercially available samples are summarized respectively in Tables 1. The thermal diffusivity values are calculated using Eq. (5).

We can conclude from this table that the difference between the numerical and experimental results is about 8 %. In fact, this difference is due to the analytical resolution which we have assumed only the first term and we have supposed that the opposite face to the impulse is adiabatic.

The values of the convective coefficient exchange are between 1 and 2.7 W/m^2K. This is owed to the fact that h is a function of the conductance of the used insulating material and environment. In fact the experience was made in different days and conditions.The numerical and experimental values of these temperatures are plotted in figure 10.

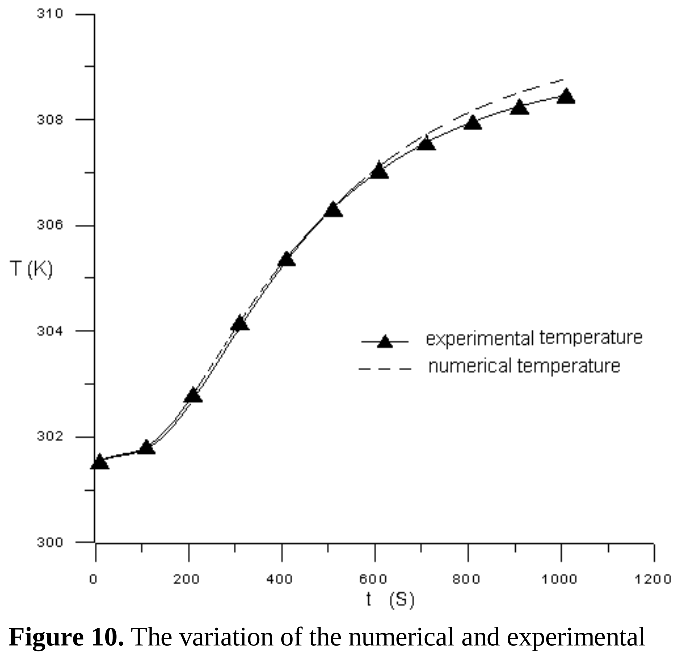

Figure 10. The variation of the numerical and experimental values according to the time cure

5. CONCLUSION

In this paper we have studied the effect of thermal diffusivity and the convective coefficient exchange h on heat transfer for different materials.

The thermal diffusivity for building material was experimentally predicted using a new apparatus. Also in this study we have compared the numerical model to the experimental data.

As a result we found that the difference between numerical and experimental results is about 8 %. When we have taken only the first term and also we have supposed that the opposite face is adiabatic in the resolution of analytical equation.

-The different values obtained for the convective coefficient exchange by numerical model are between 1 and 2.7 W/m^2K and this is due to different experimental conditions.

The main results obtained from the numerical resolution are:

- increasing the coefficient of convective exchange:
- The temperature of opposite face of material decrease.
- The establishing of the steady-state regime is rapidly attained.

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