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Thermal Performance of Sustainable Building Skins in Hot Climate

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Abstract

Modern building practice in United Arab Emirates (UAE) has resulted in constructing high-rise buildings and mega-projects characterized by glazed façades. The trend of such building development which is rapidly experienced in Dubai and Abu Dhabi has great impacts on the natural environment. Minimizing this impact and the efforts to improve the ecological performance are the main concerns of sustainable building development in the country. These ideologies have been acknowledged by architectural firms designing and constructing energy efficient buildings. This paper examines the increasing interest in integrating glass façades and living walls into sustainable buildings exposed to the UAE hot climate. The main purpose is to increase energy efficiency by improving thermal performance of building skin and reducing cooling loads. Advanced building skins, including Double Skin Façade (DSF) and Green Wall systems have been simulated and integrated into a high thermal performance building façade.

As part of a study carried out by the author, two case studies were selected to investigate the thermal performance of the building skins in the hot climate. The first case study examines the thermal transmission coefficient (U-value) of DSF, using box-window type. The second study investigates the performance of a vegetated living wall installed on a school building façades in the Emirate of Abu Dhabi. To achieve the aim of the study, various issues will be considered: sustainable performance of building skin; the impact DSF on energy efficiency in buildings; and the behavior of the green wall technique in terms of energy saving.

Keywords

Building skin, Energy efficiency, Double skin facades, Living walls, Thermal performance, UAE

1. Introduction

The hot climate of the UAE generates unique challenges to architects and engineers looking for energy efficiency in buildings. The use of transparent building facades has been increased recently throughout the country. Glazed facade system usually comes with a high air-conditioning running cost due to the higher solar gain. It is important, therefore to fit the principles of sustainable development into practice to design energy efficient buildings. In many parts of the world, including cities such as Abu Dhabi and Dubai, the design of passive cooling systems was adopted to overcome the disadvantage of using transparent façades. Buildings that are passively designed take advantage of natural energy flows and reducing heat gain to maintain thermal comfort and reduce cooling cost.

Building skin design is a major factor in determining the amount of energy used in buildings. Such design should be integrated with other aspects including material selection, daylight, heating, ventilation, and air-conditioning. The opening form, size and location have significant impacts on the efficiency of the building skin. Glazing systems have also a great impact on energy efficiency. Glazing choices are varied, depending on the design of building skin. In a hot climate, the main design strategy is to control heat gain and allow reasonable visible light transmittance for views and daylight. In cold climates, the strategy is to reduce heat loss and allow desirable solar radiation to enter the space (Straube and Straaten, 2001). Construction details and materials of the building skin also play an important role to guarantee the required level of thermal performance, which has to do with reducing thermal transmission coefficient (U-value); the lower the U-value, the better the insulation.

In terms of energy efficiency, the use of double skin façades (DSF) has gained increasing popularity to overcome the disadvantages of transparent building façades, since it can provide about 30% reduction in energy consumption (Glicksman *et al*, 2001). In hot climate, DSF strategy can reduce heat gain and cooling loads while allowing in daylight and natural ventilation. However, it can reduce heat loss in cold areas while still capturing solar gain. The use of vegetation on the external skins is also adopted in hot climate to increase energy efficiency in buildings and reduce environmental impact. Plants can be considered as a solar barrier and absorb a significant amount of solar radiation. The decreased temperature on the green surfaces on building skins can be achieved by decreased heat gain caused by the green wall; the evaporative cooling caused by the irrigation water; and heat resistance due to low thermal conductivity of the plants acting as heat insulators. This technology can reduce peak time indoor air temperature by at least 5°C for the month of July, and reduce the peak air conditioning energy demand by up to 20% (Haggag *et al*, 2012). It also contributes directly to LEED credits since it covers issues like sustainability, energy saving, air quality, and sound reduction.

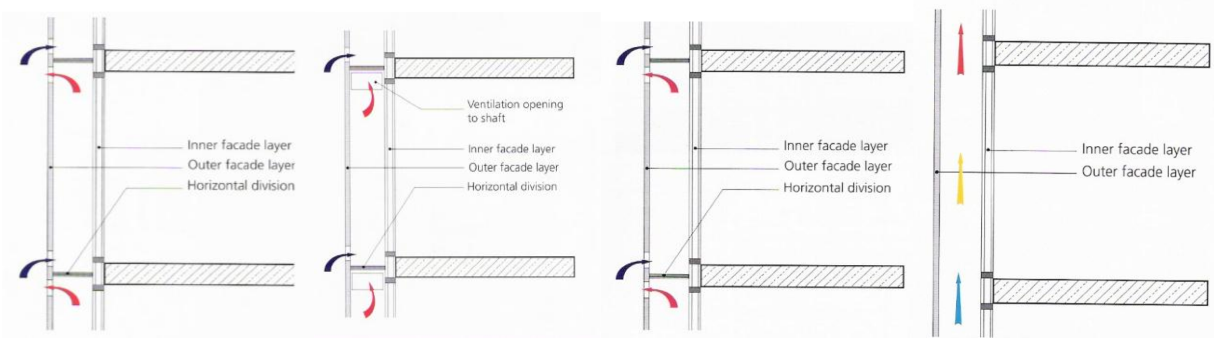
2. Performance of Sustainable Building Skin

Sustainable building skin is the practice of increasing energy efficiency in buildings, while reducing building impact on the environment (Wheeler and Beatley, 2004). It plays an important role on the overall energy performance by controlling heat transfer and solar radiation. It has to balance the need for ventilation and daylight, and provide thermal protection appropriate to climatic conditions. A natural passive cooling system is an option for sustaining building skins and reducing air conditioning costs. About 30% of the unwanted heat usually comes in through the building roof, and more than 40% through windows and external walls. To minimize the effect of radiant energy, a reflective waterproof coating and installation barriers are essential. This can reduce heat gains by about 25% (Reid, 2001). Green walls can also reduce heat gain and their surface temperature. Previous studies have shown that the external surface of a green wall is up to 10°C cooler than an exposed wall; therefore the U-value for the green wall is usually lower and helps to reduce cooling loads.

Natural ventilation helps remove heat and maintains indoor temperatures close to outdoor temperatures. This strategy only works when the inside temperature is higher than outside temperature. In hot climates, buildings designed for passive cooling strategies ensure the maximum cross ventilation. East and west walls should have minimum openings in order to prevent the effect of the low angle sun-rays. However, north and south walls should have enough windows to allow cross ventilation. A thermal chimney can be used to ensure ventilation by creating a warm zone with an exterior outlet (Roehr and Laurenz, 2008). The use of DSF strategies provides better natural ventilation and thermal insulation, facilitates daylight and increase noise control. The ventilated cavity space between the two layers of glazing provides greater thermal insulation in both hot and cool climates. This could be accelerated by a ventilated shading system situated in the cavity. This system can have almost the same effect as an external installation, and will be much more efficient than internal shading behind solar-control glass (Oesterle *et al*, 2001). The following sections focus on the thermal performance of the DSF and Green wall as intelligent building skins in terms of energy efficiency.

3. Thermal performance of the Double Skin Façades

DSF is a special type of building skin in which two or three layers of glazing are separated by airspace (cavity). In most cases, the airflow through the cavity is driven by natural flow aided by wind pressure differences or by mechanical fans (Straube and Straaten, 2001). The most popular construction types of DSF are: the box-window system, the shaft-box façade, corridor facades, and the multi-story façade (figure 1) (Oesterle *et a*l, 2001). The box-window type has a single-glazed external skin, contains openings to ventilate the cavity and indoor spaces. An additional mechanical system could be supplied to achieve the high level of thermal performance. The cavity between the two skins is divided horizontally and vertically, according to the construction modules and the floor height. This system is suitable where the level of external noise is high. The shaft-box system is similar to the box-window with a continuance vertical shaft that extends over multiple stories. The airflow, which increases thermal performance level, is directed through openings located in the external skin. This system is not recommended for high-rise buildings, since the height of the stacks is limited (Oesterle *et al*, 2001).



Box window System   Shaft-box system   Corridor facade system   Multi-storey façade

Figure 1: Typical Sections of DSF Systems (Oesterle *et a*l, 2001)

The corridor façade system is different from the above two systems. The cavity between the two skins is separated horizontally by floor divisions at the level of each floor. This system is suitable where there is a need for acoustical treatment, fire protection, or for natural ventilation. In the multi-story façade system, the cavity space is adjoined vertically and horizontally without any intermediate divisions. Openings are situated near the ground floor and others near the final roof to ventilate the cavity. The airflow comes from the bottom of the façade through a motorized damper to adjust the ventilation rate. This system is commonly used where the level of external noise is high, a glazed façade without openings is required, and where it is possible to use a mechanical form of ventilation (Oesterle *et al*, 2001). The construction of the DSF usually provides better solar protection that can reduce the effect of the external heat and cooling loads. The additional layer of glazing can reduce the insulation by about 10%. Further reduction could be achieved by placing shading devices within the cavity space (Oesterle *et al*, 2001). Reducing cooling load can be achieved by using a solar-control coating, reflective glazing, shading devices, and ventilated cavity space (Straube and Straaten, 2001).

4. Analytical Study: The Use of Double Skin Façades

Despite its advantages in terms of energy efficiency, the use of the DSF strategies is limited in the UAE. The construction cost of the DSF is always high, comparing to single skin façade. However such intelligent façades may allow trade-offs with building systems including cooling and heating systems. To get a clear picture of the real economic incentives of using DSF, an analytical study was carried out as part of a research project entitled "Thermal performance of double skin façades in hot and arid climates" [Haggag 2005]. The methodology of the study was based on interviews with building designers and maintenance engineers; simulation of single glazed façade; and simulation of double skin façades. Renaissance Dubai Hotel, which is located nearby Dubai International Airport was selected as a case study. The building is characterized by fully glazed DSF. It consists of an outer single glazed panel fastened to aluminum frames; inner double glazed operable windows with internal blinds, and a 40 cm cavity between the two skins (figure 2). The cavity is divided horizontally and vertically along the structural columns and between the individual windows. The horizontal dividers are covered by laminated sheets which act as horizontal shading devices and help to avoid sound transmission.

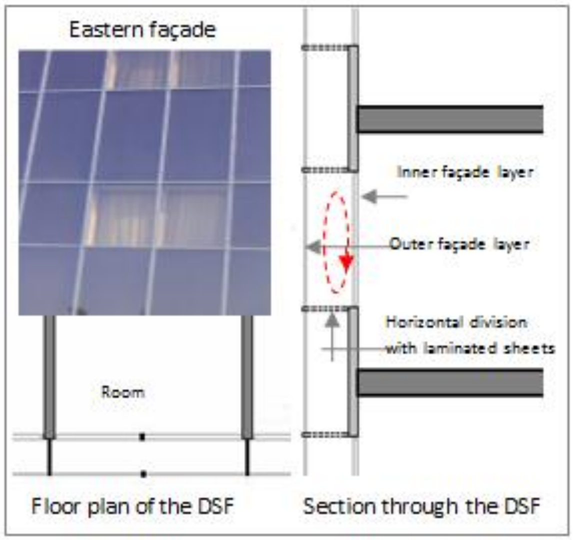


Figure 2: DSF of the Renaissance Dubai Hotel, Dubai

The comparative analysis of the performance of various glazing technologies with the performance of the used DSF showed that the solar heat gain coefficient for DSF with shading devices is between 0.09 and 0.30 W/m^2 (see table 1). This level of solar control can be achieved by a typical double glazing unit with reflective coatings, but at the cost of much higher thermal transmission, and lower natural light transmission. On the other hand, the use of clear double-glazing would result in a solar heat gain coefficient much higher than a DSF and hence a higher cooling load. The U-value of the used DSF was found to be in the range of 0.9 – 1.4 W/m^2.

Table 1: Thermal Performance of different façade systems

Façade type	Heat Gain Coefficient W/m^2	Thermal transmission coefficient (U-value) W/m^2
Masonry wall	<0.03	<0.40
Double glazing single skin facade	0.30 – 0.40	1.1 – 1.5
Double glazing single skin with reflective coating	0.07 – 0.20	1.3 – 1.5
Double skin vented with laminated shades in cavity space	0.09 – 0.30	0.9 – 1.4

It has also been concluded that this type of DSF has an acoustical insulation that is far better than that of a conventional double glazing single-skin façade (8-10 db difference). The study emphasized that the airflow inside the cavity and the divisions between the outer and inner skins play an important role not only in thermal performance but also in sound control. As a result, the use of DSF provides low U-value, less energy consumption, high visual transmittance, and high level of sound control. The study emphasized that the advantages of the DSF depend mainly on the characteristics of the site, the design of the façade, and the function of the building. Generally, the use of DSF can provide sun protection and cooling load reduction; improve thermal comfort and provide daylight; enhance natural ventilation; reduce operating costs by optimizing the daylight-thermal trade-offs; and improve indoor environments (Blasco et al, 2004).

5. Thermal Performance of Green Wall Systems

The term of green wall is used for both living walls and green façades. Living walls, or vertical gardens are consists of pre-vegetated panels or integrated fabric systems that are fixed vertically to a structural wall (Caplow et al, 2008). There are different forms of living walls, the most popular are the modular wall; vegetated mat walls; bio-filtration walls; and landscape walls (Kontoleon, and Eumorfopoulou 2010). Green façades are made up of climbing plants that growing directly on a wall or supporting structure. The plant grows up the wall while being rooted to the ground, in intermediate planters or on the rooftops. Rigid panels and cable systems can be used to hold vines off the wall surface.

The use of green wall increases the performance of building skin in terms of energy saving and provide a wide range of positive impacts on the environment. Moreover, green wall technology can protect building surfaces and extend the lifespan of the building skin by reducing surface temperature, and using appropriate techniques such as waterproof living wall panels. This protection comes mainly from keeping rain off the building while allow moisture to escape, reducing the expansion and contraction of building materials, and protecting walls against wind and solar radiation. Green wall technology helps buildings become more energy efficient and helps to reduce the urban heat island effect, absorb storm-water, and leads to reduced carbon emissions (Caplow et al, 2008). Previous observations indicated that green walls reduce the heat gain, and their surface temperature is lower than an exposed wall. Previous study investigates that the external surface of a green wall is up to 10°C cooler than an exposed bare wall, therefore the U-value for the green wall is usually lower and helps to reduce cooling load. In winter, green wall techniques act as insulation layer by moving air between the plant and the wall and creating a buffer against the wind which reduces cool air coming in. Other study investigates that the shading effect of green wall reduces cooling loads by approximately 20%, resulting in an 8% reduction in annual energy consumption (Reid, 2001).

Wong et al pointed out that green wall techniques can reduce the maximum temperatures of a building by shading walls from the sun by a range of 25- 50%. Moreover, large amounts of solar radiation can be converted into latent heat which does not cause temperature to rise. With the insulation effect of vegetation, temperature fluctuations at the wall surface can be reduced from between 10 °C and 60°C to between 5 °C and 30 °C (Wong et al, 2010).Vertical greenery system has a visual impact on buildings, and can help to address the lack of green space in urban environments.

6. Analytical Study: the Use of Living Wall System

As a case study of a research project carried out by the authors (Haggag *et al*, 2012); Liwa International School was selected to investigate the performance of the living wall in the hot climate. The school is located in Al-Ain City, UAE and was converted from conventional to green building in 2010 through the installation of a vertical greenery system on its facades. Other green strategies including roof mounted thin film photovoltaics array and grey water recycling system have been adopted. A vegetated living wall was installed on the building façades, using standard modular units made of plastic, installed connectively on the façades with drip irrigation pipes and plant foliage (figure 3). Two identical class rooms have been tested: one with external bare walls and the other with green walls. Both are facing the Eastern direction and constructed from hollow block covered with cement plaster. To determine the temperature regulation effect of green wall on indoor spaces, temperatures at four locations were recorded for both bare and green walls, using “DaqPRO” data loggers: a) ambient air temperature (1m outside from the external wall); b) external surface temperature; c) internal surface temperature; and d) internal air temperature (1 m inside from the internal wall). As a result, the external surface temperature on bare wall stayed around 54ºC while the temperature on green wall remained at an average of 48 ºC. A similar trend was observed for the rest of the duration of experiment in the months of June and July with slight variation in the magnitude of the temperature regulation. The reduced external surface temperature on green wall is an evident to yield a reduced internal surface temperature compared to bare wall. The internal surface temperature on the bare wall stays at an average of 52 ºC while the internal surface temperature on the green wall stays at 46 ºC which shows a similar trend and magnitude of temperature regulation as of external wall. The study emphasizes that since the internal wall is in thermal communication with the indoor air through convection, the drop in internal surface temperature yields a drop in indoor ambient temperature with green wall compared to bare wall (the difference is 6-8 ºC).

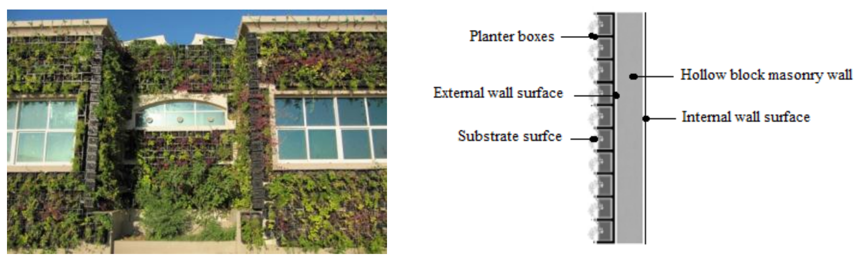
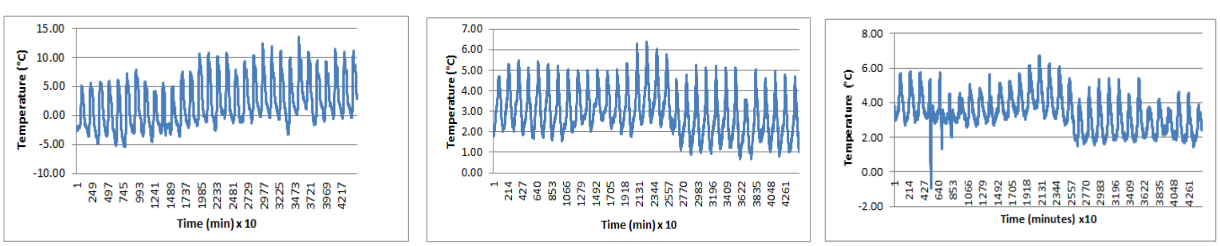


Figure 3: The Living Wall System of Liwa International School, Al-Ain City, UAE

The diurnal external, internal and indoor temperature differences between bare and green walls are shown in figure 4. The diurnal external surface temperature difference is consistently above 5ºC reaching up to 13 ºC at peak time (figure 4–a). It is recognized that the temperature difference between the bare and green walls is positive during day time however at night time the temperature difference is negative. This shows that in a colder climate, the insulation effect of green wall can be exploited to keep the heat absorbed during day time indoors from escaping to outdoors and keep the space warmer for thermal comfort and reducing heating load. In hot climates, this would tend actually reverse the ambient cooling effect at night by reducing external wall cooling rate. Figure 4–b shows that the internal surface of the green wall remains cooler than the internal surface of the bare wall with a consistent difference of 4-6 ºC during peak day time, and 1-2.5 ºC during lowest peak night time. It means that in both day and night conditions the green wall maintains lower temperature than bare wall. This can be recognized also in figure 4–c where the diurnal indoor ambient air temperature difference between bare and green walls is almost 6 ºC during peak day time.



a) external surface temperature difference b) internal surface temperature difference c) indoor ambient air temperature difference

Figure 4: Diurnal temperature difference of the bare and green wall, Liwa International School

The test room was simulated in eQuest using Al Ain weather data from 2011 entering construction details of the test room. The indoor control conditions were kept at 25 °C temperature with no humidity control and 0.5 Air Changes Per hour (ACH). This ACH generally prevails in tested space due to air infiltration in this type of constructions. The result shows in table represent cooling load for each month with a reasonably realistic profile of cooling need with peak in month of June and July which is in accordance with the weather conditions in Al Ain City.

In order to compare the results, the heat removal rate to keep the indoor air at control temperature were calculated from the measured outdoor temperature and the fixed indoor comfort temperature of 25° C with following equation

$$Q^{\cdot} = \rho V^{\cdot} c_p \Delta T$$

Where Q. and V. are heat removal and volume flow rate of air respectively, ρ, c_p and ΔT are the air density, specific heat capacity and temperature difference between outdoors ambient and indoors control temperature. The simulation and experimental results are shown in figure 5. The results show that simulated and experimental temperature is in close agreement with a percent difference of approximately 9 %. This shows that the measured temperatures for the test room with bare wall were accurate enough to validate the experiment results.

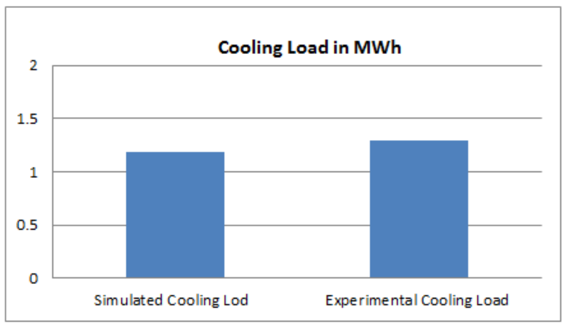


Figure 5: Comparison Between the Simulated and Experimental Cooling Load for the case with Bare Wall

Finally heat gain from the test room with green wall was processed to calculate the cooling load of the building with green wall and is compared with the cooling load of the bare wall in figure 6. The results show that the cooling load reduced from 1.35 MWh to 1.07 MWh resulting in 20.5 % energy saving for cooling because of the green wall.

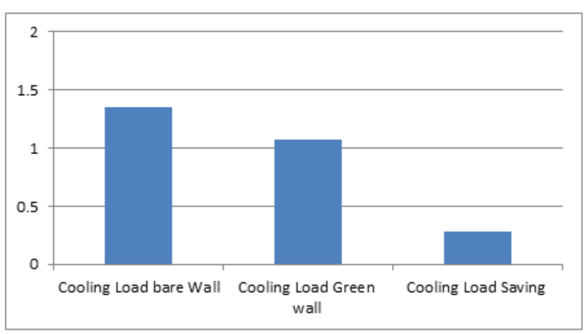


Figure 6: Comparison of Experimental Cooling Load for the Bare and green walls

It is important to emphasize that the external and internal surface and ambient temperatures being high enough and permit for a higher need of mechanical cooling for heat removal or passive interventions to reduce heat transfer into the building. By intervening the heat transfer with green walls , all temperatures are consistently lower than the bare wall which indicates the reduced heat transfer and resulting cooling effect produced by the green wall, however indoors temperatures attained through this single intervention 43 °C - 45 °C are still far from the comfort temperature of 26-28 °C which shows that although green wall reduced the cooling load by certain amount , they cannot be sufficient and need the mechanical cooling alongside with green wall. The mechanical cooling load can be reduced by integrating a vertical greenery system into double skin façade. A vertically vegetation layer could be integrated into the cavity space of the DSF. This technique is known as vertically integrated greenhouse (VIG) (Caplow et al, 2008). The main idea of this system is that the installed plants can act as shading devices which help absorb heat and liberate it within the cavity. This technique helps to strengthen the economic justification of the DSF system.

7. Conclusion

Improving the ecological performance of building development and minimizing the negative impact on the environment are the main concerns of urban development in the United Arab Emirates. The use of intelligent glazing façades and passive cooling systems has gained increasing popularity in many cities to increase energy efficiency in buildings and reduce environmental impact. Double Skin Façade and living wall strategies were successfully adopted in sustainable buildings exposed to the UAE hot climate to improve thermal performance of building skin and reduce cooling loads. DSF strategies provide better natural ventilation and thermal insulation, facilitates daylight and increase noise control. The solar heat gain coefficient for DSF vented with laminated shading devices can reach 0.09 W/m2. The additional layer of glazing and cavity space reduce the insulation of the building skin by about 10%. Further reduction could be achieved by placing shades that help in absorbing heat and liberating it within the cavity. To increase energy efficiency of the DSF, a vertically vegetation layer can be integrated into the cavity space. Installed plants act as shading devices that help in reducing heat gain and increasing energy efficiency. The decreased temperature on the green facades, in general are achieved by decreased heat gain; the evaporative cooling; and heat resistance. This strategy can reduce peak time indoor air temperature by at least 5°C for the month of July, and reduce the peak air conditioning energy demand by up to 20%. Additionally, it contributes to LEED credits since it covers issues like sustainability, energy saving, air quality, and sound reduction. Despite their advantages, DSF and green wall systems require extensive energy analysis and economic justification to get a clear picture of the real economic incentives.

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