Analysis of the Thermal Characteristics and Energy performance of Electro Chromic Glazing window

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Abstract— Windows and shading devices occupy an essential part between inside and outside environment of buildings, for providing interior air quality and optimization of lighting and HVAC energy consumption. This paper aims to perform the thermal performance of double pane Electrochromic window (ECW) using Finite Element Method and the energy performance using the Building Information Modelling (BIM) tool. The thermal model of the ECW is simulated in COMSOL Multiphysics. Double pane glass with and without electrochromic (EC) layer is analyzed to obtain the average and maximum surface temperature between the top and bottom layers of the glazing. It is observed that the maximum temperature gradient is observed with EC layer. The energy performance with a double glazing and ECW for warm and humid climate is evaluated using eQUEST DOE tool. A 30 % reduction is observed in the annual energy consumption with an ECW compared to that with a double-glazing window. In addition, during the monthly evaluation of energy consumption, there is 10% reduction with the ECW compared to baseline. The appreciable thermal characteristics and the energy performance of the EC glazing proves it to be an alternative solution for normal window glazing in automated buildings for thermal comfort and lesser cooling load demand.

Keywords— Double pane Electrochromic, Finite Element Analysis (FEA), temperature characteristics, COMSOL Multiphysics, eQUEST, Building Information Modelling (BIM), Energy consumption

I. INTRODUCTION

In India the building sector consumes 35% of the total energy consumption and it grows annually at a rate of 8% per year. The main consumers in the building energy are heating and cooling units and lighting sector. In this scenario, it is necessary to consider sustainable resolutions for energy savings. Windows plays as a key factor in energy losses in a residential or an industrial building [1]–[3]. But windows have a major role in allowing daylight inside the interior space[4]. Recent studies proved that a proper designing of a window always associates with the visual comfort, thermal comfort, and well-being of the occupants. Excess incident daylight passing through the glazing causes an increase in the load on HVAC unit and skin damages[3], [5]. Mostly the Indian climate belongs to sub-tropical category with hot summers, light winters and humid rainy seasons. Uncontrolled solar radiation penetrated through the glazing increases the total energy consumption of the building and causes discomfort to the occupant. Few years back glazing market paved the way for switchable glasses for developing a sustainable building in future [6]–[8]. Pioneers in the glazing industry has already designed and developed various adaptive, robust, and customized control algorithms for daylight control through the windows. From the literature, we came to know that application of this smart glass in both residential and industrial buildings aids occupant’s comfort and reduction in energy consumption.

Dynamic glasses come with different types. Widely market available smart glasses are Electrochromic(EC), Suspended Particles Device (SPD) and Liquid Crystal devices (LC) [8], [9][10], [11]. Electrochromism is the optical property of a material where the shading or mistiness of a material changes when a voltage is applied [6], [12]. Thus, an electrochromic brilliant window can impede bright, noticeable, or (close) infrared light immediately and on request.

Electrochromic materials switches from high optical transmittance in the bleached state to highly absorptive in the coloured state and this switching is reversible as well [13]. The total absorption of light of wavelength for an EC in the bleached state depends upon the product of their respective absorption coefficients and thicknesses. The absorption in the bleached state also depends upon the colouration efficiencies of the layers and the proportion of residual charges left behind due to incomplete redox reactions in the materials. The total combination of all these factors in a range of wavelengths determines the absorption of light in the bleached state, which, in turn, determines the effectiveness of the EC glazing window. A two-dimensional time varying finite element analysis was established to simulate large area Li ion electrochromic devices [14]. In addition, the impact of voltage variation due to spreading resistance also examined. Mathematical model for a 2D simple glass window was established to simulate the heat transfer [15]. In addition, the impact of glass thickness on solar heat gain and shading coefficient were also studied. Design of EC model based on Adaptive Neuro-Fuzzy Inference System was performed to study the glazing performance [16]. Models was able to exhibit good performance even with noises. However, the model lacks relevant physical and chemical processes took place in the EC device. Tungsten Oxide, generally represented as WO_3, is most widely used oxides of metal for EC windows [16]. This is primarily because of its high intercalation efficiency, durability, and colour modulation efficiency in the visible range. WO_3 is easily the most popular choice for the EC electrode in EC glazing windows also because of the ease of manufacture of electrodes with it. So far a very few mathematical models of EC glazing are available in the literature [13]–[16]. Finite Element Analysis method is a modelling method that is used to solve problems, which consists of boundary value in engineering and mathematical physics. In boundary value problems, differential equations are needed to be satisfied by some dependent variables in the regions of the known domain and certain conditions. FEM is useful in solving problems with complex geometries and large numbers of material property variables where analytical methods become too complicated or even impossible to apply. The geometrical complexity of the domain makes it extremely difficult to obtain the exact closed-form solution. FEM uses computational techniques and numerical methods to find the solutions with high accuracy. COMSOL Multiphysics [17] is a powerful software, which provides an interactive environment for creating models and solving all kinds of engineering and mathematics problems.

BIM enables immediate and accurate comparison of different design options, thereby assists in the development of more efficient, cost-effective, and sustainable solutions [20]– [22]. BIM can also facilitate the analysis and comparison of various energy performance alternatives to help facility managers to dramatically reduce environmental impacts and operating costs. BIM has been increasingly adopted in the Architecture, Engineering, Construction (AEC) industry since its inception in the 1970s, yet the implementation of BIM has not been fully exploited. Another major benefit for application of BIM is storing and organizing the energy-related building information. For example, real-time energy monitoring systems generate information regarding the home energy consumption, temperature, and occupancy where such information need to be stored in an organized way under proper thermal zone, equipment, and building components. There are various BIM software tools for analysing the energy performance of the building such as eQUEST, Energy Plus, TRYNSYS, Autodesk Revit, etc.

In order to study the performance of EC glazing in a real time scenario, it is necessary to examine the variations in glass surface temperatures. Inside and outside glass surface temperature speaks about the solar heat gain in the indoor spaces. This paper is majorly focuses into the finite element analysis of EC glazing to study the temperature characterizes and the energy performance via eQUEST of the same. The temperature characterizes has been done for double pane glass with and without EC coating. The energy performance of ECW is compared with double-glazing with warm and humid climate.

II. METHODOLOGY

A. Finite Element Analysis (FEA) method with COMSOL Multiphysics

COMSOL Multiphysics uses Finite Element Analysis (FEA) technique with the help of a variety of numerical solvers [19]. This software has the capability to solve several studies like transient or steady state, linear or non-linear state, frequency response etc. with postprocessing tools. COMSOL uses FEA technique to evaluate the solutions for all the dependent variables and uses these solutions to calculate additional derived variables as desired by the user. General steps for FEA are pre-processing and post processing. Pre-processing is used to give the geometric properties as well as material properties to the model. Postprocessing involves the interpretation of the solution.

The first law of thermodynamics governs the heat transfer, which is commonly known as the principle of conservation of energy, shown in equation (1).

$$\rho C_p\left(\frac{\partial T}{\partial t}+(u\cdot\nabla)T\right)=-(\nabla\cdot q)+\tau:S-\frac{T}{\rho}\frac{\partial\rho}{\partial T}\left(\frac{\partial p}{\partial t}+(u\cdot\nabla)p\right)+Q \quad (1)$$

Where,
T - absolute temperature (K)
ρ- density (kg/m3)
S - strain-rate tensor (1/s)
Cp - specific heat capacity at const. pressure (J/(kg·K))
q - heat flux by conduction (W/m2)
u - velocity vector (m/s)
p - pressure (Pa)
τ-viscous stress tensor (Pa)
Q - heat sources other than viscous heating (W/m3)

$$S=\frac{1}{2}\left(\nabla u+(\nabla u)^T\right) \quad (2)$$

Density and velocity are related, since the equation (1) assumes that mass is always conserved.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0 \quad (3)$$

According to the Fourier's law of heat transfer, conductive heat flux (Q) is proportional to the temperature gradient. From equation (2) and (1) and ignoring the viscous heating and pressure work puts the heat equation into easy form, as shown in equation (4).

$$\rho C_p \left(\frac{\partial T}{\partial t} + (u \cdot \nabla)T\right) = \nabla \cdot (k\nabla T) + Q \quad (4)$$

K is the thermal conductivity.

The equation (5) defining the conductive heat transfer is obtained if the velocity is zero:

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k\nabla T) = Q \quad (5)$$

The total incoming radiative flux(G) is named as the irradiation(G). The total outgoing radiative flux is known as the radiosity(J). The radiosity is the sum of the reflected radiation and the emitted radiation, which is given by the equation (6).

$$J = \rho G + \varepsilon \sigma T^4 \quad (6)$$

The net incoming radiative heat flux is then given by the difference between the irradiation and the radiosity, given by equation (7). Incoming heat flux is represented by q.

$$q = G - J \quad (7)$$

Using Equation (6) and (7), the net incoming heat flux into the opaque body depending on G and T, which is given by equation (8).

$$q = (1 - \rho)G - \varepsilon \sigma T^4 \quad (8)$$

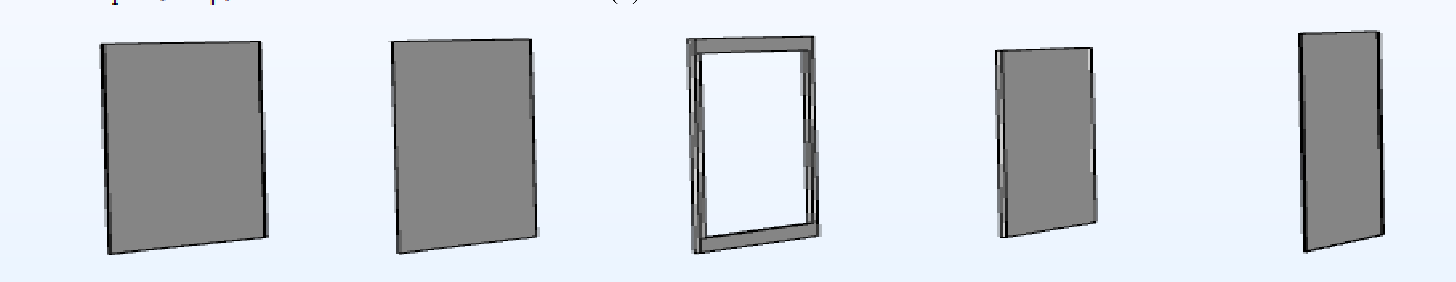

Figure 1 Different layer of double pane window (from left onwards) Glass pane, EC layer, Al Spacer, Argon, and Glass pane

In Gray bodies, absorptivity and emissivity are equal, and the reflectivity can be calculated by using the equation (9).

$$\alpha = \varepsilon = 1 - \rho \quad (9)$$

'q' for ideal Gray body is given by equation (10).

$$q = \varepsilon(G - \sigma T^4) \quad (10)$$

The layers are modelled in 3D. The dimensions considered are the glass thickness, glass length and glass width. The EC layer has the same length and same width as the glass but has different thickness. Al spacer and a cutout space in the middle Double pane glass window model is a multilayer setup which consists of two glass panes, EC layer, filler gas and aluminium spacer. Argon gas is generally used as a spacer in double pane glass windows. Aluminium spacer is used to provide strength to the window, and it also prevents gas from leaking out. The different layers of double pane window are showed in Fig.1 Argon gas is filled are defined. All the dimensions are adapted from previous literature [13], [17]. Table I indicates the geometric values chosen for the glass.

Table I. Geometric values

Description	Unit	Value
Glass Thickness	mm	4
Glass Width	in	30
Glass Length	in	44
EC layer Thickness	μm	200
Al Thickness	mm	12
Cut-out Length	mm	26
Cut-out Width	mm	40

The material properties of different materials used are given in Table II. The surface emissivity for glass 0.9. While that of the EC material, is 0.87. Fig. 2 and 3 shows the structure of glass models with and without EC layer. The nodes selected for the Heat Transfer analysis are, the initial value node, the Thermal

Insulation node, and selected node is the heat flux node. But in the Surface-to-Surface Radiation physics, the already present nodes are diffuse surface node and initial value node while the chosen nodes are opacity node and the external radiation source node. In the heat transfer in solid and liquid physics interface, the initial value of both domains is 20°C and the Convective heat flux coefficient for the outer side is 24(W/m^{2}K) and for the inner side is 8.3(W/m^{2}K). In Surface-to-Surface Radiation physics, the radiation source is located at the infinity with the direction perpendicular to the surface of

Table II. Material Properties

Material Property	Sym bol	Unit	Glass (Value)	EC materia l (Value)	Alum inum space r
Heat capacity	α	J/ (kg. K)	720	1000	900
Density	ρ	kg/m^ 3	2350	900	2700
Thermal conductivit y	k	W/ (m.K)	0.81	0.25	239
Surface emissivity	ε		0.9	0.87	0.09

the glass pane and its radiation intensity are 800(W/m^2). Based on these definitions, COMSOL selected the thermally insula0ted surface in the Thermal Insulation node. Table-III gives the flux and heat transfer coefficient values [17]

Table III. Flux and heat transfer coefficient value

Source heat flux	$800\,\frac{W}{m^2}$
External heat transfer coefficient	$24\frac{W}{m^2\,K}$
Internal heat transfer coefficient	$8.3.\,\frac{W}{m^2\,K}$
Initial Value	20˚C

For both with EC and without scenarios, the first mesh definition made was creating a triangular mesh on the gas surface of the double pane glass structure. This triangular mesh structure is swept onto the rest of the materials involved by using the Swept meshing option.

B. Energy performance of EC window

A test room with dimensions 4.17m X 4.17m X 2.31m located in Manipal Institute of technology, Manipal (13.3525° N, 74.7928° E), was considered for analysis [23], [24]. The 3D view of the facility is shown in Fig. 2. For the simulation purpose, among the four windows, only one window is considered. The window size is taken as 1.3m X 1.3 m. As the test room is located at Udupi, the selected climate type is warm and humid. However, this can be extended to any other climate.

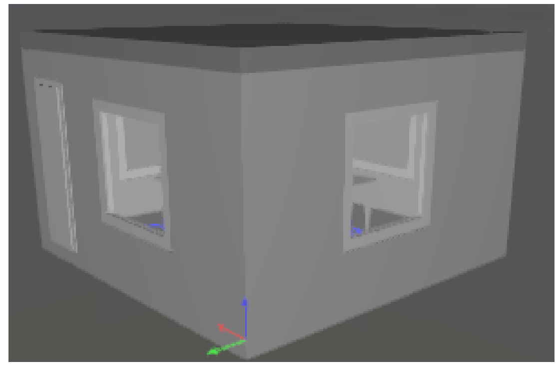

Figure 2. 3D view of the test room

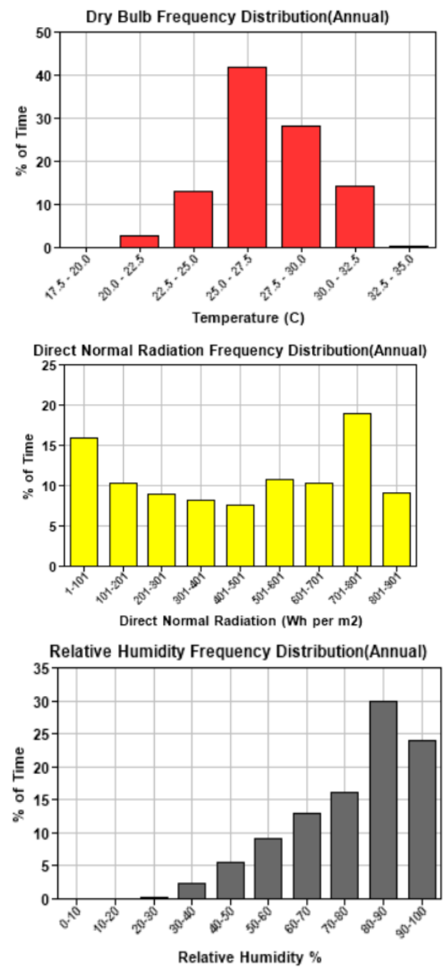

Figure 3. Annual Dry bulb temperature (top), direct normal radiation (middle) and Relative humidity (bottom) for Udupi climate

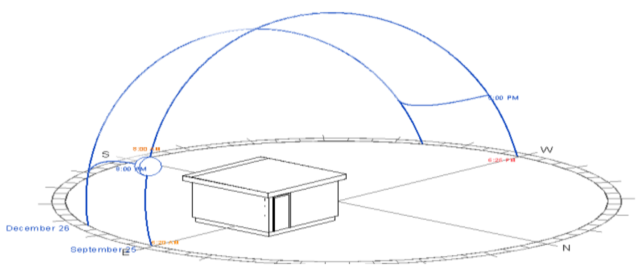

Figure 4. Solar path during 26th December 2020

The dry bulb temperature, annual direct normal radiation and relative humidity for the climate in Udupi is as shown in the Fig. 3. The sun path for the location Udupi is as shown in the Fig. 4.The dry bulb temperature for Udupi is in the range of 25- 27.5˚C for 40% of the time annually. Udupi receives a direct solar radiation in the range of 701-801Wh / m2 for 19% of the annual period. The annual humidity is found to be 80 to 90%. To analyze the energy performance (KWh), 'eQUEST,' a US Department of Energy (DOE) dynamic energy interpretation program was used. Electrochromic Absorbing Bleached (2844)/ Colored (2845) and double glazing had compared for which with the properties as listed in table 8 below:

The energy performance of the switchable glazing is analyzed using eQUEST,' a US Department of Energy (DOE) dynamic energy interpretation program. The energy performance characteristics includes U factor, Solar Heat Gain Coefficient (SHGC) and Visible Light Transmission (VLT) [25]–[28]. U factor or U value indicates the amount of heat loss through the glazing. It is directly related to the insulation capability of the material. SHGC indicates the amount of solar radiation transferred into the room through the glass. VLT gives the quantity of light transfers into the room through the glass. Two states of electrochromic glazing are available. One is Electrochromic absorbing bleached (ON state) and other one is coloured (OFF state). Comparison of a double pane EC glazing is made with a clear glass with same dimensions. Warm and humid climate suitable for the Udupi location is chosen for the analysis. Two sets of analysis were conducted to study the energy comparison between both glazing. During the first set of analysis, the glazing is kept operated for one year. Secondly, the operation is scheduled for one month. The East oriented window is considered for the simulation. In annual operation schedule, the clear glazing kept operated for all days. In this case, the EC window undergoes controlled operation. Inorder to reduce the heat gain, during summer EC window in colored/opaque state. During winter (January/February and November/December), the EC window is in bleached/transparent state for increasing the solar heat gain. In second set of analysis, the month march is scheduled to operate the glazing, since it observd that the average solar gain is high during this monrth. 8 m to 5 pm is the operating period of glazing, since it happened to be the normal office timing. Clear glazing kept operated for the entire time. While considering a single day, at east facing windows more solar gain occurs during morning time, and it is less after the mid-day time. From figure 5, it is shown that while morning the solar elevation angle is low in east direction. Hence more sunlight falls on the east oriented window. Thus, the EC window is scheduled to operate in the coloured state/ OFF state during morning time and in the bleached state/ ON stae after mid-day. The properties and the operation schedules of the glazing are as shown in the Table IV.

Table IV. Specifications of glazing used for simulation in eQUEST

Type	U-value	SHGC	VLT	Operation schedule	
				Annual	Month of March
Double glazing low-e(0.04)	0.23	0.28	0.4	ON for all year	ON for the month of march
EC (Colored) 6 + Ar 12.7 + Low-e 6 (OFF)	1.27	0.12	0.10	Colored for the summer season	Colored from 8 am to 12 pm
EC (Bleached) 6+ Ar 12.7+ Low-e6(ON)	1.27	0.6	0.66	Bleached for winter season	Bleached from 12 pm to 5 pm

III. RESULTS

A. Thermal characterizes of EC glazing

With Surface 1 of the single pane glass window facing outward and surface 2 facing inward simulation studies for temperature profile is carried out in COMSOL. With an infinite external radiation source whose intensity is 800W/m^2 which is perpendicular to the surface 1 and with the outdoor condition ranging from -15°C to 45°C and the indoor condition ranging from 15°C to 25°C. 3D image of the models for temperature profile was obtained.

The variation in the temperature of the inside and outside layer of glazing with EC is shown in Fig. 5. It shows a variation of 2.5 °C between inside and outside layers. The surface maximum and surface average values of temperatures are calculated for surface 1 and surface 2 of the double pane glass with and without the EC layer. The data obtained are tabulated and the average and maximum surface values for temperatures due to the addition of the EC layer are calculated.

Table V. Difference in average surface temperatures

		With EC		Without EC	
T_o /°C	T_i /°C	T_{1e}/°C	T2e/°C	T_{1w}/°C	T2w/°C
-15	15	-1.7327	12.337	-1.9597	11.023
-5	15	4.1878	13.301	4.1640	12.312
5	15	10.041	14.264	10.224	13.638
15	15	16.368	15.895	16.220	16.310
25	15	23.255	20.864	24.773	21.613
35	15	30.020	25.783	34.596	26.849
45	15	36.665	30.633	44.410	32.017
-15	20	-0.72256	16.637	0.92545	15.334
-5	20	5.1844	17.599	5.1852	16.621
5	20	11.024	18.560	11.232	17.946
15	20	16.799	19.520	17.215	19.306
25	20	23.419	22.096	24.911	22.836
35	20	30.180	26.982	34.735	28.062
45	20	36.822	31.817	44.551	33.221
-15	25	0.28472	20.929	0.10612	19.637
-5	25	6.1783	21.890	6.2038	20.923
5	25	12.005	22.849	12.238	22.246
15	25	17.764	23.807	18.207	23.605
25	25	23.583	24.762	25.057	25.000
35	25	30.342	28.195	34.876	29.283
45	25	36.980	32.999	44.693	34.428

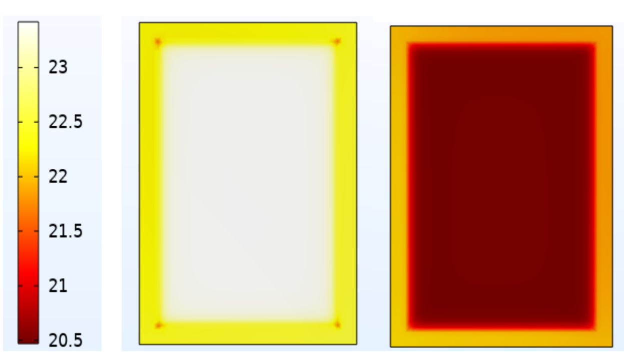

Figure 5. Temperature profile of glass window facing outside (25˚)(left) and inside(20˚C) (right

Table V and VI show the different temperatures present on the surface 1 and surface 4 of the double pane glass window with and without EC layer. T_o and T_i represent outdoor and indoor temperatures, T_{1e} and T2e represent temperatures on surfaces 1 and 4 of glass pane with EC layer and T_{1w} and T2w represent temperatures on surfaces 1 and 2 of glass pane without EC layer, respectively. Due to the presence of low thermal conductivity EC layer between upper glass layer and aluminum spacer, the heat transfer is less. However, in normal glazing, even though there is an AL spacer between the glasses, the air between the glass layers insulate the heat and hence it causes the temperature gradient. The heat conductivity of air is low as 0.025 W/mK.

Table VI. Difference in maximum surface temperatures

		With EC		Without EC	
T_o/°C	T_i/°C	T_{1e}/°C	T_{2e}/°C	T_{1w}/°C	T_{2w}/°C
-15	15	-4.4048	8.9301	-10.579	7.8171
-5	15	2.5365	11.092	-1.9278	10.320
5	15	9.3637	13.232	6.6970	12.829
15	15	16.079	15.350	15.296	15.344
25	15	22.683	17.445	23.868	17.863
35	15	29.179	19.518	32.415	20.387
45	15	35.570	21.567	40.936	22.915
-15	20	-4.0245	12.377	-10.134	11.255
-5	20	2.9108	14.533	-1.4859	13.753
5	20	9.7321	16.667	7.1359	16.257
15	20	16.441	18.780	15.731	18.766
25	20	23.040	20.870	24.301	21.280
35	20	29.530	22.937	32.845	23.799
45	20	35.915	24.981	41.363	26.322
-15	25	-3.6436	15.818	-9.6877	14.687
-5	25	3.2857	17.968	-1.0429	17.180
5	25	10.101	20.097	7.5757	19.679
15	25	16.804	22.204	16.168	22.183
25	25	23.397	24.289	24.735	24.692
35	25	29.882	26.350	33.276	27.205
45	25	36.261	28.388	41.791	29.723

B. Energy performance of ECW and double-glazing

The Fig. 6 shows the annual variation in KWh of double pane and EC window for the test room in Udupi climate. In all months, the energy consumption in ECW is 30 % reduction compared to the double-glazing. The reduction is more in the month of February compared to all other months. This graph gives an overall view of the energy performance of ECW. Windows plays major role in the building energy performance and its efficiency. ECW definitely provides a higher reduction in the cooling load of the building entity. In order to investigate more into the energy efficiency of ECW, a monthly energy analysis also performed. As previously mentioned, the energy consumption during the month of March has been considered. The Fig. 7 shows the monthly energy consumption between ECW and double glazing. Almost 10 % reduction in cooling load could be achieved with a monthly operation schedule. In both cases, replacing double glazing with ECW always provides better energy efficiency to the building entity.

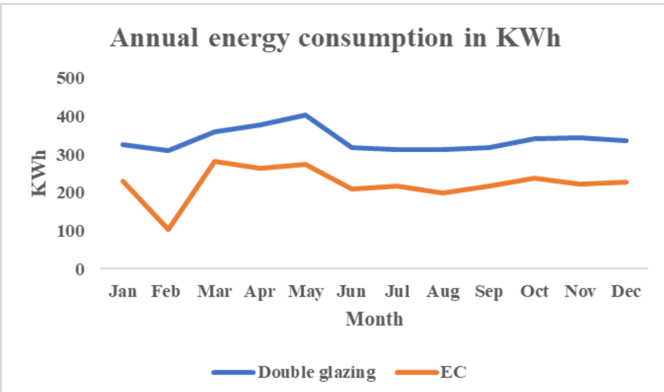

Figure 6. Annual energy consumption for EC and double glazing in Udupi climate

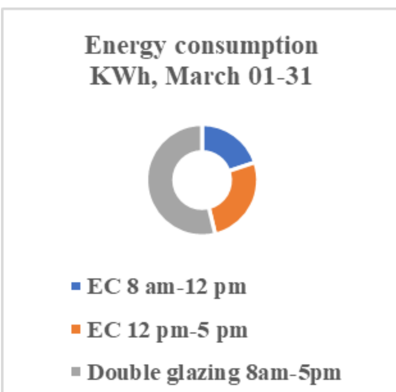

Figure 7. Energy consumption in the month of March 2021

IV. CONCLUSIONS

Electrochromic (EC) materials will reduce the wastage of energy in warming and cooling of buildings. The development and study of photo-electrochromic materials and devices for giant area window applications are ongoing. Recent interest of researchers across the globe for electrochromic devices for different spectrum of modulation of energy by the phenomena of absorbance and reflectance has extended the definition of working. EC devices are studied for the radiation modulation within the near infrared, thermal and microwave regions and colour can mean the detectors response of the wavelengths, not just the eye of the human.

The temperature characteristics and the energy performance using an ECW is analyzed in this paper. While analysing the thermal characteristics of ECW, the solar radiation is kept at 800 W/m2, assuming that the direction of radiation is perpendicular to the glazing. In FEM analysis, few assumptions were made. The solar radiation is constant throughout the analysis and it is in perpendicular to the glazing. In real time, the radiation intensity and solar angle varies. Also, the expansion of glass surfaces at different temperature has not been considered. Finally, the temperature variations occurs at the inside layers of glazing has not taken into consideration for the simulation. The thermal characteristics shows that the difference between average and maximum surface temperature is more in double pane glass with an EC layer compared to without EC layer. This makes it suitable for incorporating the EC glazing in Daylight-Artificial light integrated systems to provide thermal comfort to the occupants. Normal glazing allows the daylight entry without much reduction. This increases the inside temperature and hence the cooling load. Replacing glazing with blinds or curtain reduces the daylight harness. Since people spends comparatively more time in indoors rather than staying outside, the influence of artificial light on human biological clock must be considered [29]. Since the circadian clock depends on the light and dark pattern of natural light, uncontrolled electrical light interferes our activities [30]. It has proven that, at office spaces, where people stay longer time, the view of outside environment elevates the mood of occupants [31], [32]. In addition, proper control of EC glazing results in glare free daylit spaces [33]. Controlled entry of daylight improves the workplane lighting uniformity and ambient heat reduction, which reduces the HVAC (Heating Ventillation Air Conditioning) loads. Thus, it results in visual comfort, thermal comfort, and energy savings in the building [34].

During the evaluation of energy consumption, it is observed that, scheduled or unscheduled operation of EC windows leads to energy savings. Two different working patterns has been followed to analyse the energy performance. Fixed transparency state in normal double glazing contributes more cooling load, while compared to EC glazing in both working patterns. The first one, where the ECW kept ON for winter season and OFF for summer season brings 30 % reduction compared to baseline model. Also, when the glazing kept ON and OFF in hourly basis, the cooling load demand was more with double glazing.

Human factors tests are to be used for resolving the difficulty of whether low transmittance windows are acceptable or desirable for controlling direct source sunlight. This might remarkably reduce the dependence on an indoor window to stop direct sun rays. In addition to this progress of the EC material towards faster switching speeds, reduced colour tinted state, least transmittance, and reduction in the manufacturing costs would all be welcomed by the market which is being developed. A cheap sensor is required for supplying accurate, real-time visible transmittance data on installed EC windows. Given advancement in lighting controls, procedures to determine reliable daylighting control of electrochromic window and lighting control systems should be advanced and automated soon. This technique can deliver remarkable demand in cooling and lighting.

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