POTENTIAL OF EVAPORATIVE COOLING IN THE CLIMATE OF SERBIA

Milan LJ. ĐORĐEVIĆ*[*1], Marko V. MANČIĆ[2], Milena S. MANČIĆ[3]

[*1]Faculty of Technical Sciences, University in Priština - Kosovska Mitrovica, Serbia

[2]Faculty of Mechanical Engineering, University of Niš, Serbia

[3]Faculty of Occupational Safety, University of Niš, Serbia

[*] Corresponding author; E-mail: milan.djordjevic@pr.ac.rs

Evaluating the evaporative cooling potential primarily depends on gaining a detailed and accurate understanding of the local climate. In this study, the potential of evaporative cooling was estimated based on the bioclimatic analysis and psychrometric chart using Climate Consultant software. Bioclimatic charts were developed for 22 locations within a different climatic conditions in Serbia in order to quantify the potential of evaporative air cooling strategies for different regions. Bioclimatic charts are generated by plotting Typical Meteorological Year weather data set on the psychrometric chart along with ranges defined with human thermal comfort models. The software tool demonstrates the effectiveness of Direct and Two-stage Evaporative Cooling for defined comfort model. The percentage reduction in total cooling hours with the help of these systems varies 16.1-94.9% at the locations considered. The study also indicates that indirect system with vapor-compression second stage can provide adequate comfort cooling with significant savings throughout the cooling season. The obtained results generally recommend the application of evaporative cooling technology in air conditioning in the climatic conditions of Serbia, especially in all types of cooling systems based on fresh air. This can have significant implications for engineers when choosing a combination of cooling strategies which are appropriate for the specific location.

Key words: *evaporative cooling, thermal comfort, Climate Consultant*

1. Introduction

Buildings are the largest individual consumers of energy, and therefore also major polluters of the environment. Due to the long lifespan of buildings, their impact on the environment is longlasting and continuous and cannot be ignored. Energy efficiency in buildings is recognized as an area that has the greatest potential for reducing total energy consumption in near future, which could directly affect comfort and quality of living and contribute to environmental protection and reduction of harmful gas emissions.

The building sector is the largest contributor to primary energy consumption and greenhouse gas emissions worldwide. In the EU and U.S. buildings were responsible for about 40% of the primary energy consumption [1], while in Serbia as much as almost 50% percent of the final energy is consumed by the building sector, of which 65% is in the residential sector [2].

The most of this energy used in residential buildings is used for space heating and cooling. The energy consumption of the vast majority of these buildings is determined by how well they respond to the local climate. A full understanding of the local climate gives the designers many opportunities to explore the range of passive strategies and HVAC systems within the context of the building's location. Since climate analysis used in preliminary design is essential, designers should be supported by suitable weather-analysis tool rather than relying completely on statistical climatic data. The essence of HVAC systems design is to benefit from the favorite climate conditions in every project site using passive and hybrid strategies to achieve thermal comfort with minimum use of energy.

Air conditioning of buildings worldwide is currently dominated by conventional compression refrigeration systems. Energy consumption and Greenhouse Gas (GHG) emissions from building sector are expected to increase in the future due to global warming, especially in developing countries [3]. The *International Energy Agency* (*IEA*) forecasts highlight that the huge increase in air conditioning will have the largest and most unpredictable impact on the world's electricity grids over the next decade, and that many decision-makers do not realize how crucial air conditioning is to global electricity consumption. As a potential energy efficient alternative to the conventional mechanical vapor compression system, the evaporative cooling systems have attracted much attention for comfort cooling [4].

The evaporative cooling technique takes the advantage of water evaporation to achieve cooling effect. The principle underlying evaporative cooling is the conversion of sensible heat to latent heat. The wetted medium could be a porous wetted pad consisting of fibers, cellulose papers or a spray of water. Various evaporative cooling methods and systems are considered the most important low-cost alternative to conventional direct expansion technology due to lower energy consumption and reduced power demand at peaktimes, lower capital and maintenance costs. About two-thirds of the electrical power consumed by the mechanical vapor compression system can be reduced by switching to evaporative cooling systems in suitable climates [5].

Evaporative air conditioning technology is comparatively simple, functional, inexpensive and has both residential and commercial applications in industrialized and developing countries. It works best in hot and dry climates, but it can be used in more humid climates as well. Regions with design wet bulb temperature lower than 24ºC are natural regions where evaporative cooling air conditioning may be used [6]. Evaporative cooling units are also environmentally friendly as they work without the use of compressors and refrigerants (chlorofluorocarbons (CFCs) or hydrofluorocarbons (HFCs)). Evaporative systems operate with compleatly fresh air, which eliminates the recirculation flow and proliferation of fungi and bacteria, a constant problem in conventional air conditioning systems. The need for air conditioning systems that work with completely fresh air has become especially pronounced during the coronavirus pandemic.

Summarizing the above, it can be concluded that the evaporative cooling system has the following advantages over the current mechanical vapor compression system [6-8]**:** (1) substantial energy and cost savings, (2) reduced CO_2 and power plant emissions, (3) reduced peak demand, (4) no CFCs or HFCs usage, (5) improved indoor air quality, (6) significant local fabrication and employment, (7) life-cycle cost effectiveness, and (8) easily integrated into existing systems.

In evaporative cooling systems, heat required for evaporation of water is taken from the air around and is dependent on the wet-bulb depression of the air [6]. These systems are divided into three main groups: (1) direct evaporative cooling (DEC); (2) indirect evaporative cooling (IEC); (3)

indirect/direct evaporative cooling (IDEC). DEC is the simplest, oldest, and the most widespread form of evaporative air conditioning. This system typically uses a fan to draw hot outdoor air trought a porous wetted medium or a spray of water. The water absorbs heat as it evaporates from the porous wetting medium, and thus the air leaves the DEC at a lower temperature. In fact, dry bulb temperature (DBT) of the air reduces as it is moistened in this adiabatic saturation process. The system cannot cool down the incoming air lower than its wet-bulb temperature (WBT). The wet-bulb effectiveness could reach range between 70-95% in most current commercial DEC coolers and mainly as a function of the type and thickness of evaporative media, supply air flow-rate and working climate. Direct systems in low humidity regions typically deliver energy savings of 60-80% over vapor compression air-conditioning systems [9].

In IEC, air is divided into two streams and goes into a heat exchanger. Secondary air is cooled by evaporation, then the primary air is cooled by indirect contact with secondary air. For a typical indirect evaporative heat exchanger, the primary air (or product air) and the secondary air (or working air) flow in separate passages. The secondary air acts as a heat sink by absorbing heat due to water evaporation. An IEC system is able to produce the cool air without moist change. IECs can cool the intake air below the wet-bulb temperature and typically have the wet-bulb effectiveness of 60-80%. Due to higher energy losses in IEC process, it is less efficient than DEC. While the greater number of air passes increases the pressure drop and the required fan power, the high effectiveness extends the geographic range where the IEC can fully meet the cooling demand. More than 60% power saving could be achieved by this system in comparison with mechanical vapor compression systems and 55% increase in water consumption with respect to DEC systems [8]. This system can complete the gap between DEC systems and convencional compression systems as an energy efficient and environmentally clean alternate [8].

IDEC is a combination of the indirect and direct evaporative cooling systems. A tipical two-stage evaporative cooling setup consisting of an IEC stage followed by a DEC stage. Two-stage IDECs can cool air to lower temperature than is attainable with DECs, while adding less moisture to the indoor air. A first-stage (IEC) lowers both the DBT and WBT of the incoming air. After leaving the indirect stage, the primary air passes through a second stage (DEC). Figure 1 shows the schematic diagram with main components of the IDEC system and the cooling process on a psychrometric chart. First-stage cooling follows a line of constant humidity ratio as no moisture is added to the primary airstream. The second stage follows the WBT line at the condition of the air leaving the first stage. Indirect/direct systems yield 40-50% energy savings in moderate humidity zones [4]. Indirect systems with vapor-compression second stages can provide adequate comfort cooling in high-humidity zones with savings of up to 25% [10].

Much research has been conducted on the application of evaporative coolers as an alternative to the conventional air conditioning system for providing thermal comfort in different climates, especially in arid climate regions [11, 13]. The primary area of recent research into different configurations of evaporative cooling systems for different climates and applications has been experimental and numerical investigations. Fundamental aspects concerning the heat and mass transfer process of different evaporative cooling systems in different parts of the world has been presented by various theoretical and numerical models [13-18].

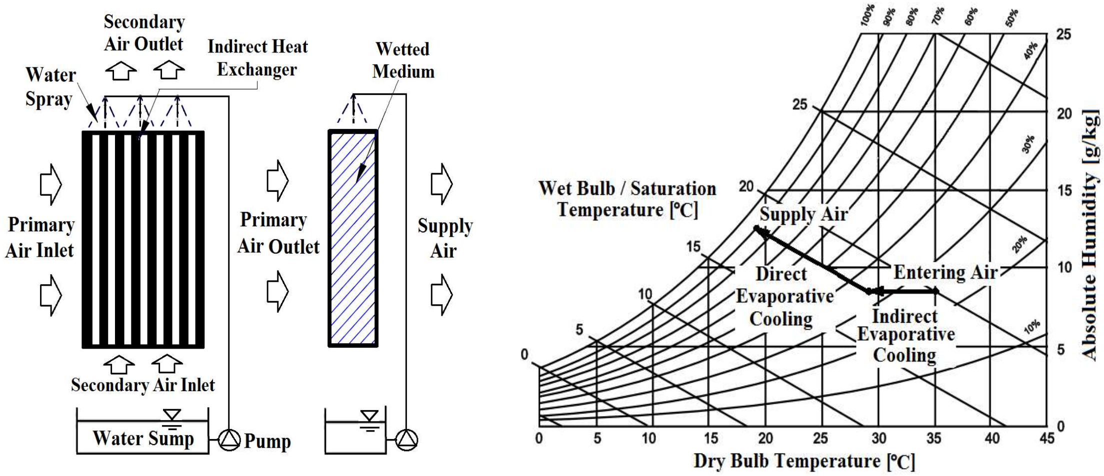

Figure 1. The IDEC: Schematic diagram (left) and Psychrometric process (right)

The limiting factor for the application of DEC is the definition of comfort, since the air humidity increases resulting in uncomfortable indoor thermal environment for humans, while the theoretical minimum temperature of cooled air is the WBT. Additionally, instability of the ambient air temperature and humidity causes unsteady operation of all evaporative cooling systems. However, technical improvements of evaporative cooling systems widen the zone of applicability so that they can be used in some comfort cooling applications as well as many commercial applications even in humid climates. Although evaporative coolers cannot be used in all countries and at all times, they are generally very much underutilized in places where they can be used successfully [6].

In general, evaporative and vapor compression air-conditioners must be compared with care because vapor compression air-conditioners can always provide full comfort, but evaporative air-conditioners cooling depends on local climatological conditions [6]. Due to low energy consumption, evaporative cooling is considered suitable for many applications like air conditioning for office and retail buildings, cinemas, sport centres, data centres, *etc*. The need for reduction in energy consumption is also relevant in industrial buildings, which have high volume and high internal thermal loads. For this kind of large facilities a sustainable alternative and the practical method to improve indoor thermal conditions and productivity of workers is represented by evaporative cooling systems. Delivering both ventilation and cooling, these systems can efficiently cool large spaces or provide spot cooling to specific areas or locations. In locations where high volumes of fresh air are required to meet the demands of occupants and local design codes, evaporative cooling can far outperform a traditional air conditioning approach.

1.1. Thermal comfort

International standards like ASHRAE Standard 55-2013 [19] and ISO 7730:2005 [20] are used for evaluating indoor thermal environments in buildings. According to ASHRAE Standard 55, the standard comfort zone on the psychrometric chart is based on the Predicted Mean Vote - Predicted Percentage Dissatisfied (PMV-PPD) model. ASHRAE standard 55 defines thermal comfort by 6 parameters - air temperature, radiant (globe) temperature, relative humidity, air velocity, occupant metabolic activity rate and occupant clothing. A comfort zone is defined by a particular combination of these 6 parameters. It has two comfort zones for summer and winter clothing and the slightly sloped temperature limits account for the fact that in dryer air people are more comfortable at slightly higher temperatures [21]. The comfort zones set boundaries for operative temperature and humidity for sedentary activity (1-1.2 met) and clothing insulation (0.5-1.0 clo), within which the indoor climate has to be mainteined. It was constructed mainly for use in air-conditioned office buildings, but is also used in evaluating the indoor climate in residential buildings.

Comfort models are defined by the human thermal response to their environmental conditions and surroundings. The comfort zone that is used extensively as the basis for structuring bioclimatic charts is the ASHRAE comfort zone [22]. The thermal comfort zone on the bioclimatic building design chart indicates the comfort boundary conditions for a particular climate and is useful in the establishment of passive design strategies for that climate. It is important to emphasize that this comfort zone is not universal, but can vary depending on the severity of the climate and conditions and adaptation tendencies of people living in that climate.

In most cases, it is impossible to achieve year-round comfort in buildings using only passive and bioclimatic design measures, so the heating or cooling needs are covered using active systems. The use of bioclimatic and psychrometric charts is considered essential in building performance simulation tools to understand and visualize the climate in relation to thermal comfort.

Bioclimatic tools are primarily psychrometric charts used for investigating whether the local climate of a certain location can provide human thermal comfort. Thermodynamic properties of moist air are key determinants of thermal comfort within a building and are important in the design of air-conditioning systems, which makes psychrometrics an indispensable part of any passive and climate responsive design process.

1.2. Climate of Serbia

Climate data analysis, aimed at formulating building design guidelines, often involves presentation of the annual patterns of the main climatic factors affecting human comfort and the thermal performance of buildings in various forms. A uniform system based on the Köppen-Geiger classification [23] is commonlly used to clasiffy and understand a large variety of local and regional climate characteristics, as well as passive building strategies that are appropriate for each climate. This system was originally developed by Wladimir Köppen around 1900. Early versions were based on previous maps of vegetation growth, but it has subsequently been revised as more comprehensive monitored data became available. It is based on the concept that native vegetation is the best expression of climate and takes into account different latitudinal zones (based on extreme temperatures), as well as seasonality in both temperature and precipitation [24-26]. The classification still bears criticism when developing climatic zones [25], because in reality there is infinite variety in climatic conditions, but it remains the benchmark against which others are assessed. Countries usually have more than one climatic zone and it is sometimes difficult to establish the prevailing climate classification.

Köppen-Geiger climate classification map for Serbia from 1980 to 2016 [24] is shown in Fig. 2. The expected climate change and increase in temperature will significantly affect the energy consumption in the Republic of Serbia and alter the current balance of energy consumption. Higher temperatures are predicted to decrease the energy demand for heating in winter and increase the electricity demand for cooling in summer. Thus it is necessary to regulate the new constructions, incorporating the risk estimations for overheating with climate data for 2050 or even 2100, and enhance passive solutions to mitigate the waste of resources and energy. Köppen-Geiger climate classification map for Serbia from 2071 to 2100 [27] is shown in Fig. 3. Forecasts clearly indicate that climate change will strongly influence the large increase in demand for air conditioning in Serbia in the future.

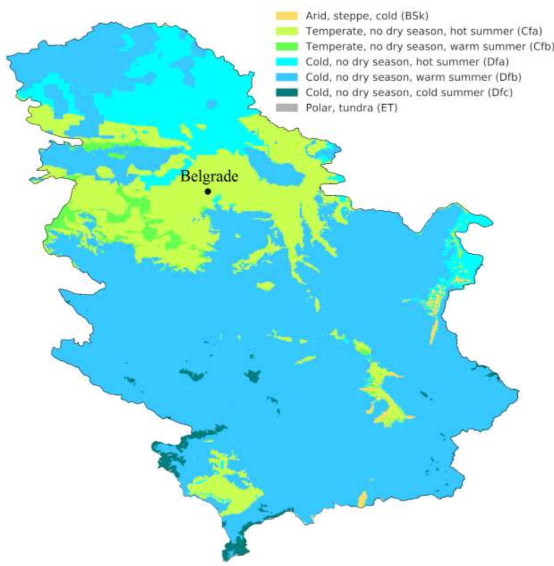

Figure 2. Koppen-Geiger climate classification map for Serbia (1980-2016)

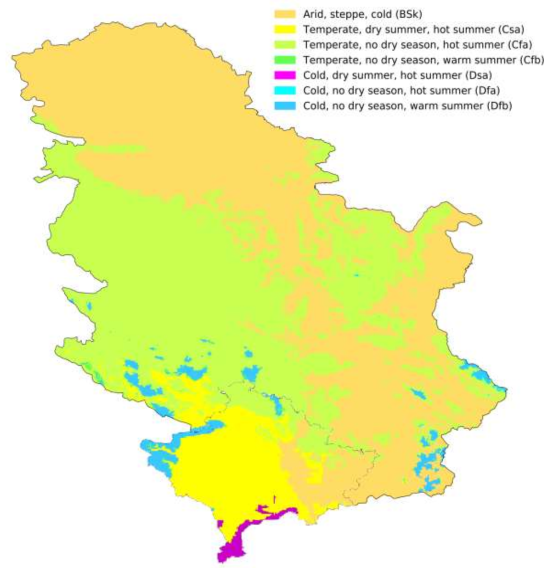

Figure 3. Koppen-Geiger climate classification map for Serbia (2071-2100)

2. Results

The use of energy efficient cooling systems depends primarily on gaining a detailed and accurate understanding of the local climate and the characteristics and purpose of the building facility itself. In this research, an energy design tool known as Climate Consultant 6.0 software [22] was utilized to analyze the potential of evaporative cooling for 22 urban locations all over Serbia. Climate Consultant is a a graphic-based software tool for visualizing building energy implications of climates, with an embedded expert system that automatically interprets each location's climate data. This was obtained from the psychrometric chart, which is an irreplaceable tool for understanding and establishing thermal comfort of the occupant.

Climate Consultant software offers four thermal comfort models, and in this research work the ASHRAE standard 55 [19] was selected for defining the thermal comfort of the occupant. This model is appropriate for the Serbia climate because it has two zones of comfort - one for the heavy clothing of the heating periods and another for the light clothing of the cooling ones.

The software reads local climate data for all 8760 hours per year in EPW format files available for stations around the world. On the psychrometric chart each dot represents the temperature and humidity of each of the 8760 hours per year (Fig. 4).

Different Design Strategies are represented by specific zones on this chart. The percentage of hours that fall into each of the 16 different Design Strategy Zones gives a relative idea of the most effective passive heating or passive cooling strategies. The definition of each of these zones on the psychrometric chart has been explained in detail in literature [28]. In this research, only 6 zones are observed, namely: Comfort, Sun Shading of Windows, Direct Evaporative Cooling, Two-Stage Evaporative Cooling, Dehumidification and Cooling, add Dehumidification if needed (Fig. 4).

In this step, hourly meteorological parameters of 22 locations were graphically printed on the psychrometric charts using hourly data of appropriate EPW files. The comfort zones and zones depicting different design strategies were then superimposed. All analyses and statistics were carried out on this psychrometric charts from which comfortable, potentially comfortable and uncomfortable periods have been determined. This can show how to design energy efficient hybrid cooling system that can benefit from favourable external climate conditions to create comfortable indoor environments.

For the purpose of brevity, only the Psychrometric chart showing cooling and/or dehumidification hours for the Belgrade climate is shown here (Fig. 4). Hours covered by the selected strategies are green, whereas hours out of the range are red. It is important to note that for dry bulb temperature above 23.8°C, zones of action consider that spaces are shaded. Belgrade's climate has mainly temperate continental characteristics, categorized as Cfa (Humid Subtropical Climate) according to the Köppen climate classification [29].

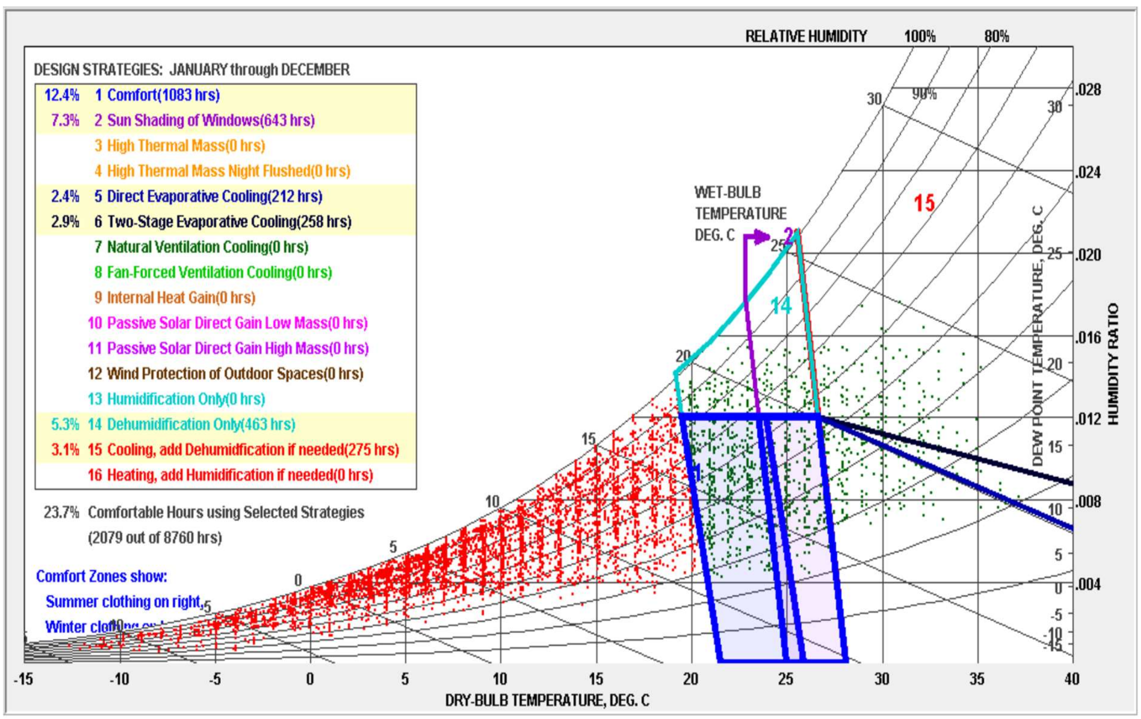

Figure 4. Psychrometric chart indicating cooling and/or dehumidification hours for Belgrade

The yearly potential values of hours that fall into each of these 6 selected zones and cooling strategies for 22 urban locations all over Serbia were shown in Figs 5-10. These numbers will be changed by changing the comfort models or any other default criteria. Many of these strategies can be used concurrently, for example Sun Shading works with all cooling strategies.

Base comfort potential indicates the proportion of time during a year when comfort conditions prevail for a given location without the application of any passive or active strategies. The most effective passive cooling strategie for comfort improvement is Sun Shading. It has the advantage of being able to be combined with all the other cooling strategies. The Psychrometric Chart shows the number of hours when it is assumed that Sun Shading is provided, but this hours are not added to the total number of comfortable hours because shading itself cannot guarantee comfort. Definitions of Comfort and Sun Shading Zone, as well as their annual potential values (in hours) for the 22 locations have been presented in previous research [30].

Dehumidification Zone is displayed on the Psychrometric Chart directly above the top of the Comfort Zone (Fig. 4). It represents the case where the indoor air is within the dry bulb comfort range but is too humid and so would need to have moisture removed. On any hour when outdoor temperature is above the comfort range and is not in any other cooling strategy zone, by default that hour falls into the zone where some type of artificial cooling is necessary [31]. However, if it is still too humid, than some form of dehumidification will be necessary. These conditions are represented by a strategy named Cooling, add Dehumidification if needed. Since it is commonly assumed that a conventional air conditioner also provides dehumidification to create comfortable conditions, these two categories are combined to show the total number of air conditioner operating hours. The total annual cooling and dehumidification hours for the 22 locations in a decreasing order of magnitude were shown in Fig. 5. A general trend from the spatial distribution of annual needs for cooling and dehumidification cannot be inferred, except that locations at higher elevations have lower needs, as expected. The applicable cooling hours for DEC and Two-Stage IDEC are presented in Figs 6 and 7, respectively, while their percentage reductions in total cooling hours are shown in Figs 8 and 9.

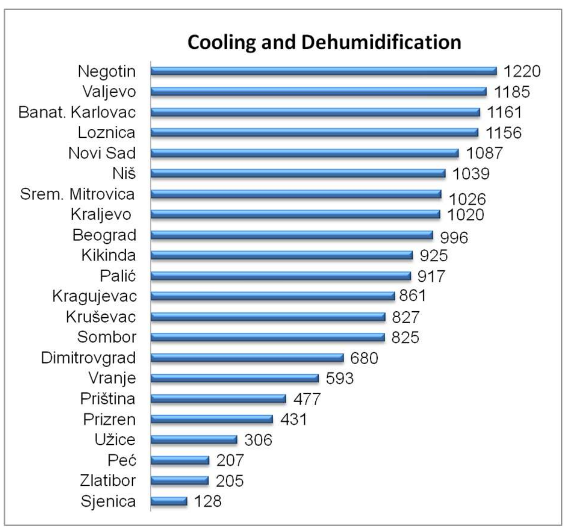

Figure 5. The total annual cooling and dehumidification hours

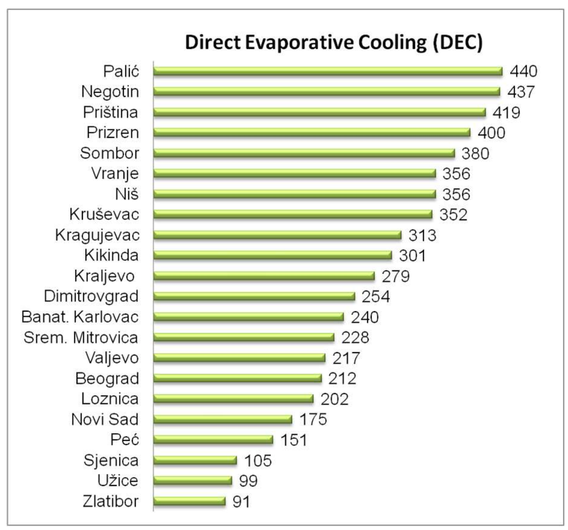

Figure 6. The applicable cooling hours for DEC

DEC Zone is defined automatically by the highest and lowest WBT that fall within the comfort zone [31], (Fig. 4). This zone is defined automatically by the highest (20°C) and lowest (6.6°C) WBT that fall within the chosen comfort model (ASHRAE Standard 55).

DEC has proven to be an effective strategy for saving energy and reducing CO_2 emissions. Its use has relatively high potential as the percentage reduction with DEC systems can account for up to 92% of the total cooling hours (varies from 16.1 to 92.8%). The general trend shows that locations with the highest needs for dehumidification have the lowest application potential - western locations (Valjevo, Loznica) and locations in Vojvodina (areas closer to rivers).

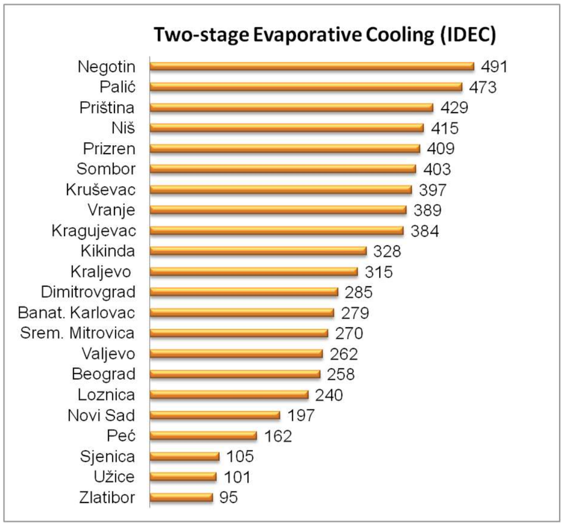

Figure 7. The applicable cooling hours for Two-Stage IDEC

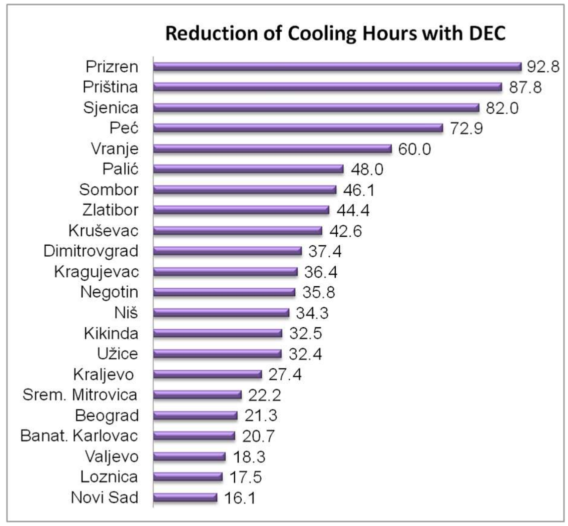

Figure 8. The percentage reduction in total cooling hours with DEC

Two-Stage Evaporative Cooling Zone is displayed on the Psychrometric Chart as a modification of the DEC Zone, where the angle of the upper boundary is increased in proportion to the percent efficiency of the Indirect Phase. In this study the efficiency of the Indirect Phase was set to 70% for all cases. The first stage uses evaporation to cool the outside of a heat exchanger through which incoming air is drawn into the second stage where it is cooled by direct evaporation.

Comfort improvements by Two-Stage IDEC are also valuable. The percentage reduction in the total cooling hours with Two-Stage IDEC systems varies from 18.1 to 94.9% at the considered locations. It could be observed that it increases the potential of DEC, but that it does not significantly affect the convenience of a particular location compared to DEC.

It is important to note that Belgrade, the capital and the largest city, does not have a significant potential for achieving comfort through evaporative cooling compared to other locations. It should also be pointed out that the locations with the greatest reduction in total cooling hours with DEC and IDEC do not have significant annual needs for cooling. Likewise, for locations in Serbia with elevation higher than 500 m (Peć, Priština, Zlatibor, Sjenica) is needless to adopt strategies for cooling and dehumidifying (mechanical vapor compression, evaporative cooling, etc.), as thermal comfort zone of the occupants can be achieved through the implementation of only passive design strategies [30].

Figure 10 indicates the proportion of time (in %) during a year when comfort conditions can be extended over the DEC by using Two-Stage IDEC. The results indicate a relatively moderate increase in cooling hours by adding the indirect stage to the direct one.

Due to lower energy savings and increased water consumption and capital cost of the Two-Stage IDEC systems compared to DEC systems, it is questionable whether there is an economic and environmental justification for using the Two-Stage IDEC systems in the climatic conditions of Serbia. On the other hand, there are clear indications that indirect system with vapor-compression second stage can provide adequate comfort cooling with significant savings throughout the cooling season.

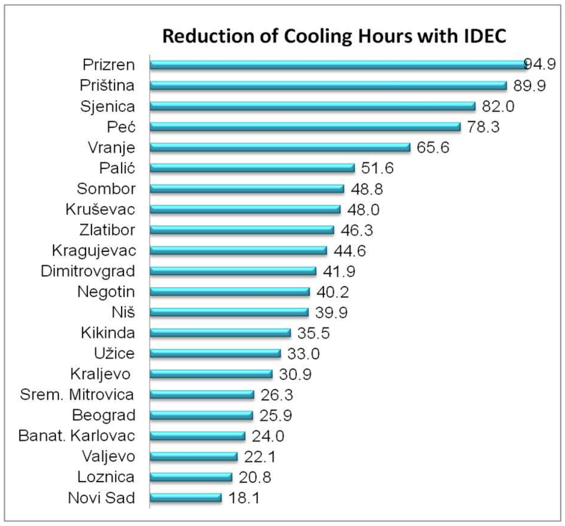

Figure 9. The percentage reduction in total cooling hours with IDEC

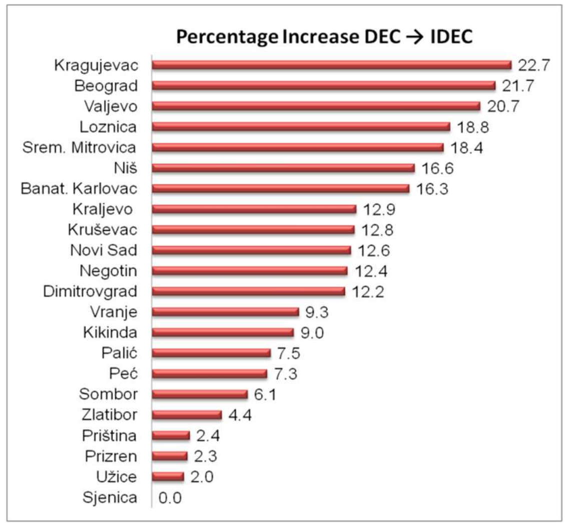

Figure 10. The percentage increase in DEC hours by using the IDEC strategy

Even under the best of evaporative cooling conditions 5.1-81.9% of the total cooling hours per year will require conventional mechanical cooling and dehumidification for considered locations.

Although evaporative coolers are capable to take over up to 94.9% from the total annual cooling hours, it should be clearly stated that the obtained values do not excactly correspont to the amount of the yearly reduced electric energy consumption, cooling load or the requested maximum cooling power. Further research is needed to estimate the precise reduction of these quantities, but previous findings clearly lead to the conclusion that evaporative cooling equipment is capable to reduce the requested maximum cooling power of the chillers, allowing the use of smaller chillers with lower investment cost.

The obtained results generally recommend the application of evaporative cooling technology in air conditioning in the climatic conditions of Serbia, especially in all types of cooling systems based on fresh air.

3. Conclusions

The viability of using evaporative air cooling depends on the particular application and on the local climatic conditions. The Climate Consultant software was used to estimate the potential of direct and combination of indirect and direct evaporative cooling for 22 locations all over Serbia. Comfort prediction with ASHRAE Standard 55-2013 thermal comfort zone revealed that the percentage reduction in total cooling hours with the help of DEC and IDEC systems varies 16.1-94.9% at the locations considered, specifically with DEC systems 16.1-92.8%, while with IDEC systems 18.1-94.9%. Even under the best of evaporative cooling conditions 5.1-81.9% of the total cooling hours per year will require conventional mechanical cooling and dehumidification for the considered locations.

Evaporative cooling systems are not only an economical alternative, they can replace conventional vapor-compression systems in many circumstances, can be used as precoolers for conventional systems, thus providing adequate cooling comfort with significant savings throughout the cooling season. Due to relatively moderate increase in cooling hours, lower energy savings, increased water consumption and capital cost of the Two-Stage IDEC systems compared to DEC systems, it is generally questionable whether there is an economic and environmental justification for using the Two-Stage IDEC systems in the climatic conditions of Serbia. This research clearly indicates that evaporative cooling equipment is capable to reduce the requested maximum cooling power of the chiller in climatic conditions of Serbia, allowing the use of smaller chillers with lower investment cost.

Policymakers should become better informed about evaporative air cooling because of the reduction in CO_2 emissions that comes from the energy efficiency of the technology, the opportunities it provides to reduce the use and emission of CFCs and HFCs, and the potential to alleviate problems of peak electricity demand during the cooling season.

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Paper submitted: 05.02.2025

Paper revised: 05.03.2025

Paper accepted: 12.03.2025