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Investigation and Optimization of Commercial Refrigeration Cycles Using the Natural Refrigerant CO_2

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Abstract--With tighter regulations on the use of Hydroflurocarbons (HFCs) due to their high GWP (Global Warming Potential), many supermarket operators are looking for alternative refrigerants. To contribute to this, the objectives of this proposed research work are to investigate the practicality, environmental benefits and economic viability of all-CO_2transcritical refrigeration system suitable for departmental stores or supermarkets. While the environmental benefits of using CO_2 as a refrigerant are clear, there is rather limited practical and technical knowledge on the design and operation of these systems. In this proposed work, the performances of the transcritical booster CO_2 refrigeration system and traditional HFC system will be compared. The models will be verified using test results from experimentation on refrigeration system using CO_2. To compare the performance of the CO_2 refrigeration system in the field, energy data from a supermarket employing a HFC refrigeration system will be used for energy simulations. The literature survey on the utilization of CO_2 as refrigerants for supermarkets refrigeration are encouraging to take up this as a research work. The CO_2 system proposed in this research may replace the existing conventional systems in supermarkets. In this paper,various experiments performed throughout the world is reviewed and studied and also an attempt has been made to bring out the importance of utilization of CO_2 as a refrigerant.
Key words: CO2, supermarkets refrigeration, GWP, transcritical and Hydroflurocarbons.

I. INTRODUCTION

A. CO_2 as A Refrigerant

CO2 is an old refrigerant that has been used since the early stages of there frigeration industry in various applications, especially those which required large amounts of refrigerant and strict safety considerations. This was the case until the 1930's and 1940's when synthetic refrigerants were introduced and then CO2 started to lose out faced with competition from the new refrigerants and was gradually replaced in all applications. The main reasons for the freewill phasing-out of CO2 are its high operating pressure (about 64.2 bars at 25ºC) and its low critical temperature of31ºC. This implied that CO2 systems had containment problems. Furthermore, when condensing close to and rejecting heat above the critical temperature the systems suffered loss in cooling capacity and efficiency. The technologies available at that time could not solve the problems attached to the use of CO2.Synthetic refrigerants were considered as safe for many decades, but it proved otherwise for the environment. From this perspective, as a natural substance, CO2 is an ideal choice; it is a by-product of the chemical industry and using it in refrigeration applications can be considered as an additional step before its inevitable release into the atmosphere. As a naturally existing substance in the atmosphere its long-term influence on the environment is very well investigated and we can assume that there are no unforeseen threats that CO2 poses for the environment. As a result of its surplus in the atmosphere and the inescapably large scale of its current production CO2 is inexpensive and available. Nowadays technologies can provide the tools to harness the high working pressure of CO2, running and controlling the system in the super critical region. In 1989, Professor Gustav Lorentzen suggested in a patent application (Lorentzen, 1990) that CO2 could be used in a cycle that operates in the trans-critical region where the high pressure can be controlled by a throttling valve, which he proposed as a solution for mobile air conditioning application. This was a breakthrough that revived interestin CO2 as refrigerant and revealed new horizons to the refrigeration industry and the relevant research institutes. Since the revival of CO2 as a refrigerant, a considerable amount of research work has been conducted to investigate the "new" refrigerant's thermodynamic, thermal and transport properties and to try and explore new areas of application.

B. CO_2 in Supermarket Refrigeration

The early application of CO2 in supermarket refrigeration was as a secondary working fluid in indirect systems. Some of the main reasons for using CO2 in indirect system arrangements are the simplicity of the system and the possibility of using components for other refrigerants to build its circuit.

Due to the widespread interest in CO2 as an alternative to synthetic refrigerants in the two major refrigerant consuming applications, i.e. mobile air conditioning and commercial refrigeration, components which are specially designed to handle CO2 have become increasingly available and competitive in price. This has broadened the possibilities of usingCO2 in arrangements other than indirect systems so that its favorable characteristics can be utilized effectively. About ten years after the firstCO2 installation, other arrangements such as cascade and multistage systems have also been applied commercially.

II. PREVIOUS STUDIES ON CO_2AS A REFRIGERANT IN SUPERMARKETS

SamerSawalha[1] studied theoretically and experimentally investigated different aspects of the application of CO2 in supermarket refrigeration. Theoretical analysis has been performed using computer simulation models developed to simulate CO2 indirect, NH3/CO2 cascade, CO2 trans-critical and direct expansion (DX) R404A systems. The models supported the selection of the CO2 system solutions to be tested experimentally and facilitated the design of NH3/CO2 cascade and trans-critical systems test rigs. Performance evaluation and systems' optimizations have also been carried out. In order to verify the findings of the theoretical analysis an experimental evaluation has been performed whereby a scaled-down medium size supermarket has been built in a laboratory environment. NH3/CO2 cascade and trans-critical systems have been tested and compared to a conventionalR404A system installed in the same laboratory environment. Experimental findings have been compared to the computer simulation models. In supermarket refrigeration applications, safety is a major concern because of the large number of people that might be affected in the event of leakage. Therefore, a computer simulation model has been developed to perform calculations of the resulting concentration levels arising from different scenarios for leakage accidents in the supermarket. The model has been used to validate some of the risks associated with using CO2 in the application of supermarket refrigeration. Results of the experiments and the computer simulation models showed good agreement and suggest that the NH3/CO2 cascade system is a more efficient solution than the analyzed conventional ones for supermarket refrigeration. On the other hand, CO2 trans-critical solutions have efficiencies comparable to the conventional systems analyzed, with potential for improvements in the trans-critical systems. From a safety point of view, the analysis of the calculations' results clearly shows that using CO2 in supermarket refrigeration does not create exceptional health risks for customers and workers in the shopping area. Studies conducted in this thesis prove that the CO2 systems investigated are efficient solutions for supermarket refrigeration.

From the study, it is clear that usingCO2 in supermarkets refrigeration does not engender exceptional health risks for the customers and the workers in the shopping area. Nevertheless, it is recommended that CO2 detectors are installed in the shopping area, especially in places where leakages are possible and high local concentrations are expected in the case of a leak. It must be pointed out that even if the CO2 charge and the size of the supermarket's shopping area and machine room are identical to the modeled example, the case of every supermarket must be considered individually, taking into consideration geometrical variations and the location of the distribution lines. Evidently, safety requirements such as proper ventilation and an alarm system are essential in the machine room.

ZineAidoun, Mohamed Ouzzane[2]previously developed model has been used to show that there are cases where refrigerant circuiting is necessary. Most hydro fluorocarbons can accommodate only limited tube lengths due to excessive pressure drop in refrigeration coils as is shown here with R507A, commonly employed in supermarkets. A study of the effect of circuiting on coil operation has then been performed for three different configurations of evaporation paths, using CO2 as a working fluid. The basic unit consisted of a single circuit forming the whole coil unit. The other two configurations had, respectively, two and three circuits corresponding to the same total area and tube length as the basic unit. Comparison between these three units was made using the basic unit as a reference. The analysis was based on the numerical model that calculates incrementally parameter distributions for air across the coil and for refrigerant inside the tubes. Circuiting which consisted in defining refrigerant flow paths and varying flow rates within the coil was shown to affect performance and general operational coil behavior, particularly the refrigerant pressure drop and the corresponding temperature glides. It is possible to use longer circuits with CO2 (in comparison to other refrigerants), therefore reducing their number for a given capacity

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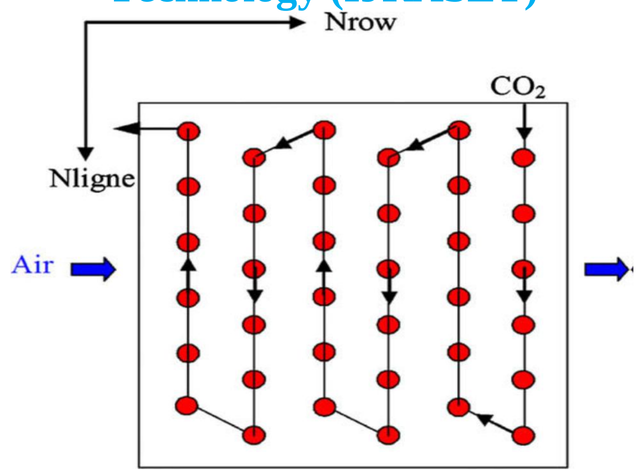


Fig. 1.Typical refrigeration circuit.

The model used in the present study was previously developed and validated for the design and simulation of wavy fin heat exchangers. It has been used to handle geometry and operating parameter variations, including simple circuitry arrangements. Circuiting arrangements are based on the fact that refrigerant must be submitted as much as possible to air conditions in a uniform manner as well as distributing the flow rate between the circuits. This was shown to contribute to parameter distribution uniformity and better operational performance. Preliminary calculation examples considered in this paper were based on a typical coil used in refrigerating cabinets. The coil capacity is approximately 3.5 kW and the inlet air temperature is _24 _C. Refrigerant R507A used in these conditions needed several reduced length circuits while for CO2 a single circuit was sufficient to obtain the same or an even smaller temperature glide. More specifically, over a tube length of 90 meters, the temperature drop was DTev = 1.8 _C. Further simulations were then performed to compare 2 circuited configurations to a reference unit using CO2 as refrigerant. For a pre-defined geometry and operating conditions, some advantages offered by the use of coil circuiting arrangements have been demonstrated, among others:

– Air temperature behind the tube passes is approximately constant and its distribution across the coil is generally more uniform. This is beneficial with R507A and particularly true with
CO2.

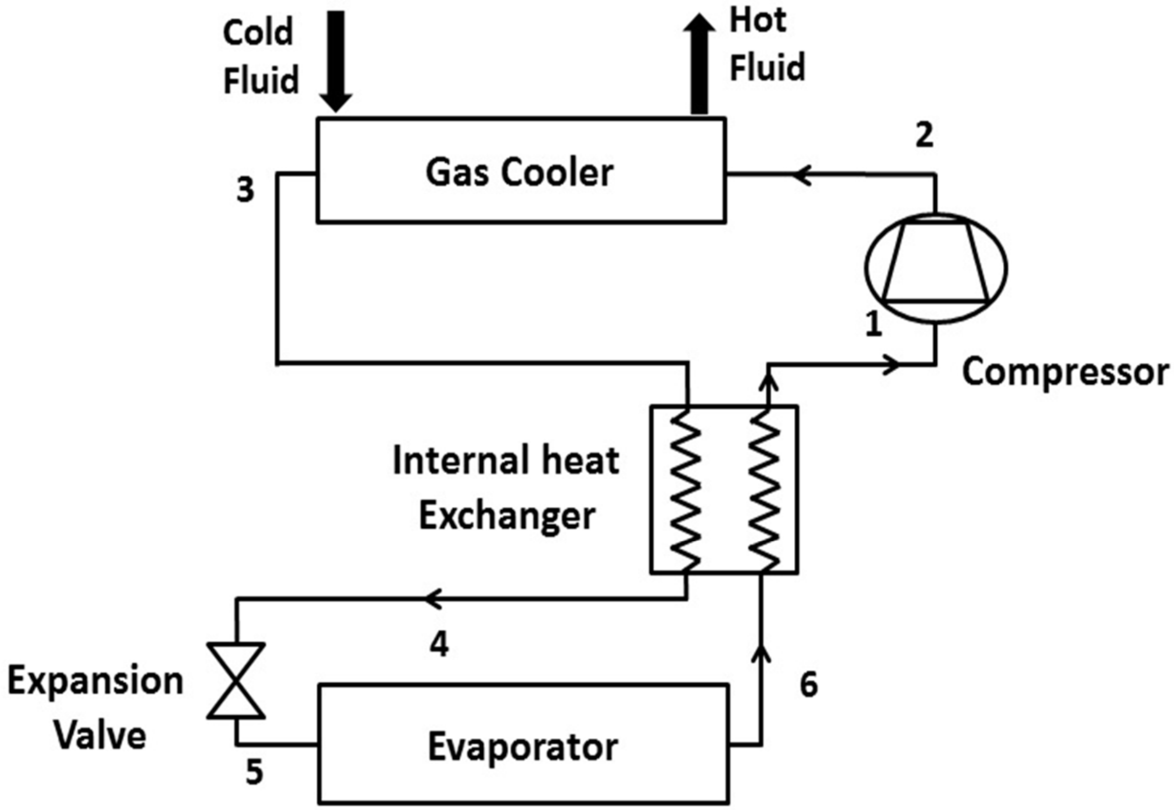
A. Pressure drop for CO2 is very small in comparison to other refrigerants ordinarily used in current systems such as R507Awith correspondingly small temperature glides. This has a positive impact on the air temperature distribution within the freezing cabinet.

B. It is possible to use longer circuits with CO2 (in comparison to other refrigerants), therefore reducing their number for a given capacity. This greatly simplifies the coil geometry, impacting positively on refrigerant distribution and the cost of the coils.

C. For the cases considered the number of circuits, their lengths and location in the coil were not optimized for a capacity improvement which has yet to be investigated further.

D. Preliminary and general recommendations about flow and circuiting arrangements can be made when geometry and operating conditions are known.

A.B Pearson[3] studied now a days wide range of equipment choices facing the designer of industrial CO2 refrigeration systems. Secondary loop, cascade and trans critical plants all have their place and can offer unusual benefits to the designer and the operator of the plant. Most research work, particularly on transcritical systems is looking at small systems for domestic and commercial applications. Some of these findings can be scaled up to industrial plant, but in other cases better designs become more appropriate. In a few cases the small scale solution simply does not apply to large scale plant. This paper addresses the particular challenges of designing industrial systems and offers insight into ways of using existing equipment. It also suggests some ideas for future development to capitalize on the advantages offered by carbon dioxide. From his study carbon dioxide offers a wide range of benefits, but within fairly tight constraints on operating temperatures and pressures. At higher temperatures cascade systems are also more expensive and less efficient than the best of alternative systems, such as two-stage ammonia plant. However as higher pressure compressors and ancillary components become available this situation will undoubtedly change. Compressors suitable to be the high pressure side of a two stage transcritical system will probably be available on the open market in sufficiently large sizes to suit industrial applications within the next five years. There are numerous new ways to gain maximum advantage from this technology, many as yet undiscovered. This provides a number of opportunities for further study in component design and application. It is to be hoped that these opportunities will be pursued in industrial systems, not just in laboratory-scaled experimentsK.S. Rawat [1], V.S. Bisht[2], A.K. Pratihar[3][4]the Montreal and Kyoto protocol are two frameworks towards a single goal of environment safety. Theseprotocols suggest prohibiting the usage of synthetic refrigerants to prevent ozone layer depletion and control global warmingas well. Such conditions encourage us to consider CO2 as a working fluid for refrigeration and air conditioning systems. Inthis paper, thermodynamic analysis of CO2 based transcritical cycle is presented to show the effect of various operatingparameters of transcritical cycle. The operating parameters considered in this study include heat rejection pressure in gascooler, evaporator temperature and gas cooler exit temperature. At the end, three useful correlations that yield the optimalheat rejection pressure in gas cooler, the associated maximum COP, and optimum compressor discharge temperature in thetranscritical cycle are presented.



Thermodynamic analysis presented in this paper leads to following conclusions:
COP of the system decreased with increase in gas cooler inlet temperature of external fluid. Hence gas cooler inlet temperature of external fluid should be low which depends on ambient conditions. An increase in evaporator temperature resulted in increase in COP of the system. Effectiveness of internal heat exchanger has no effect on COP of the transcritical system.
To optimize the COP, a regression analysis has been performed that could be useful to refrigeration engineers for setting optimum heat rejection pressure in gas cooler.
A case study[5]by Navigant consulting (5)had been carried out f operating experience with a transcritical carbon dioxide (TC CO2) booster refrigeration system at Delhaize America’s Hannaford supermarket location in Turner, Maine. This supermarket, which began operation in June 2013, is the first supermarket installation in the U.S. of a TC CO2 booster refrigeration system. We compare refrigeration system performance to that for a supermarket having nearly identical layout and refrigeration loads, in a similar climate and of similar vintage, that uses a conventional hydro fluorocarbon (HFC) refrigerant. Delhaize provided the sub metered and utility data used to generate the performance summaries herein.
Table I.1 compares selected design and climate characteristics of the Turner supermarket and a Hannaford supermarket located in

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Bradford, VT that uses a direct-expansion HFC-407A refrigeration system with heat reclaim. When making performance comparisons, we made analytical adjustments to account for certain design differences between the two stores. We did not, however, adjust for climate differences, as they are small.

Table I.1 Selected Design and Climate Characteristics for the Turner and Bradford Supermarkets

	Turner, ME (TC CO2)	Bradford, VT (HFC-407A)
Refrigeration System Capacity (MBtu/Hr.	740	748
Building Peak Heating Load (MBtu/Hr.)	1298	1644
Heating Degree Days/Yr. (65°F Base)1	7406	7541
Turner store features requiring data adjustment	Pump house Water treatment system Emergency power circuit Generator	

compares the electricity consumption of the refrigeration systems of the two stores on a monthly basis from October 2013 to August 2014. The TC CO2 system's electricity consumption was of a comparable magnitude to that for the conventional refrigeration system. Overall source energy consumptions (electricity and propane) for the two supermarkets are also comparable.

This study shows relative parity between the energy consumption of the baseline and TC CO2 stores, a reduction in climate impact, and potential additional operating cost benefits attributable to the use of a TC CO2 system. This suggests that TC CO2 supermarket refrigeration systems is a viable alternative to HFC-refrigerant-based systems on a case by case basis when considering climate impacts, especially in cooler climates. The TC CO2 booster system at the Turner supermarket showed month-to-month energy consumptions within +/-20% of the conventional HFC system at the Bradford store, and the Turner store exhibited a 15% overall reduction in climate impact compared to the baseline HFC store in Bradford. Additionally, the system showed no issues with reliability or utility when compared to legacy HFC systems such as that used in the Bradford store. The study also explored other considerations – such as the difficulty of retrofitting this technology and the limited availability of components and installation professionals. While these are challenges that must be addressed by any adopter of this technology, during the course of this study Hannaford was able to largely mitigate the effects of these possible roadblocks through proactive efforts and frequent communication with its suppliers and contractors.

Despite the fact that TC CO2 refrigeration technology is not yet proven to be an omnipresent solution with clear benefits in all applications, it warrants consideration.

III. CONCLUSIONS

The above study reveals that, CO2 can be efficiently used as a refrigerant in supermarket in order to reduce global warming potential. In this area a vigorous research is required to establish an optimum insulation to the piping to minimize heat transfer to and from the surroundings to increase the system performance. Research is required to establish optimum insulation levels to the piping between components to minimize heat transfer to and from the ambient and between components to increase system performance.

The expected main barrier to the widespread application of CO2 booster refrigeration systems in supermarkets is the high cost of the equipment compared to that of a traditional HFC system .In this work it is also necessary to reduce equipment cost also

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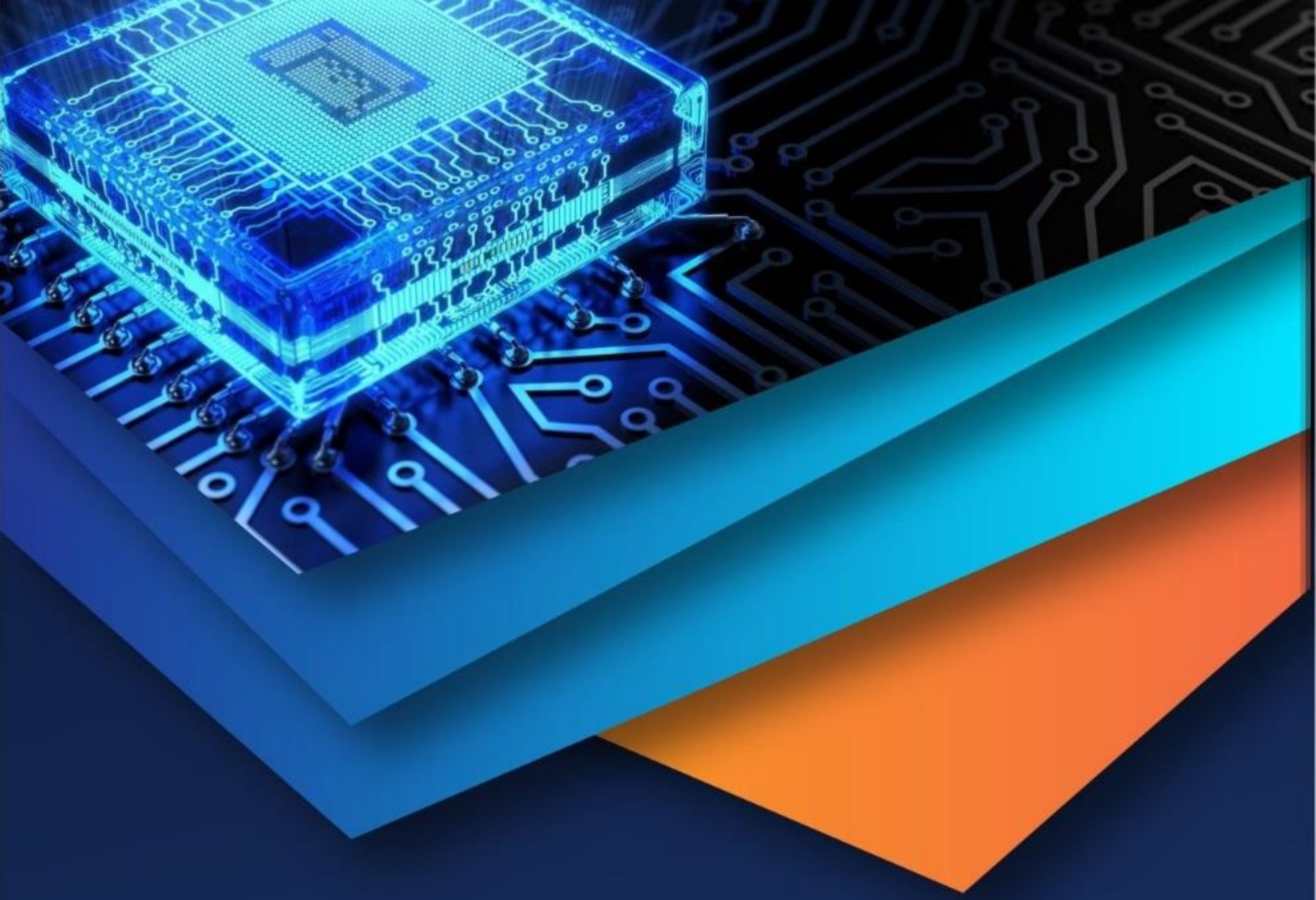

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