

**TECHNOLOGICAL POTENTIAL OF SMALL SCALE
ICE THERMAL STORAGE BASED AIR CONDITIONING
SYSTEM IN THE GENERATION PHASE FOR HOTEL &
ENTERTAINMENT
INDUSTRY OF SRI LANKA**

R.W.S.M. Sampath Godamunne

(148614L)

Degree of Master of Science

Department of Mechanical Engineering

University of Moratuwa

Sri Lanka

December 2018

**TECHNOLOGICAL POTENTIAL OF SMALL SCALE
ICE THERMAL STORAGE BASED AIR CONDITIONING
SYSTEM IN THE GENERATION PHASE FOR HOTEL &
ENTERTAINMENT
INDUSTRY OF SRI LANKA**

R.W.S.M. Sampath Godamunne

(148614L)

Thesis submitted in partial fulfillment of the requirement for the degree
Master of Science in Building Services Engineering

Department of Mechanical Engineering

University of Moratuwa
Sri Lanka

December 2018

DECLARATION

The research work submitted in this dissertation is my own investigation except where otherwise stated. This dissertation has not been accepted for any degree and not concurrently submitted for any degree in a university or any other institution.

R.W.S.M. Sampath Godamunne

I endorse the declaration by the candidate.

Prof. R. Attalage

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my principal supervisor Prof. Rahula Attalage for his continuous & very sincere tireless expertise guidance and direction throughout this research project. I am very much thankful to all the lecturers who gave me wealth of knowledge during the course of Building Services Engineering. Further I am very much thankful to various industry experts whom I met during this research project. I would like to express my sincere thanks to my colleagues of the course who generously shared their knowledge and experiences with me.

Finally I am very much thankful to my wife, children & parents for their encouragement, support plus patience during the period of my work for this research project.

ABSTRACT

Demand for electricity during a day, varies with the time due to various factors. Electricity demand of Sri Lanka for a typical day could easily be divided into three main categories. One segment characterizes a very high sudden demand increase during later in the evening, and sharp decrease of the demand during the mid night until the next day early morning time and average daily demand during the day time. As a remedial action in facing this change of demand, electricity service providers generally encourage users to reduce the demand through different measures and also shift their consumption during the high demand period to the low demand period. This is achieved by introducing different electricity tariffs based on the time of the day. As Air Conditioning systems demand considerable percentage of building electricity consumption, Cold Thermal Storage technologies is an ideal candidate for electrical load shifting applications of buildings. This study explores the technological feasibilities and also reviews the engineering economics of building small scale Ice Thermal Storage based air conditioning system in the generation phase which has average capacity of 32 Ton Hours. The development of small scale thermal storage based air conditioning system is progressed through a detailed research work and final design was reviewed of its economic feasibility to be used for hotel rooms & 100 capacity movie theaters under Hotel & General electricity tariff structures respectively.

This study further investigates in particular the ice building process in a water filled, limited length horizontal rectangular enclosure with the constant temperature glycol circulation system at the top & bottom surfaces. The rates of ice building on top and bottom surfaces were mathematically modeled based on the equations published by Et al. P. Bhargavi & Et al. Liang Yong. The dimensionless equations were then converted to dimensional and set of equations were derived to find the ice thickness Vs time, temperature profile along ice thickness at a given time and several other associated parameters necessary to calculate the heat transfer during water freezing. The goal was to find the maximum achievable ice thickness during 6.5 hours period and total energy extracted by the glycol circuit. Three glycol temperatures of -12C, -6C and -3C were considered and 3 data sets were built.

By considering a given glycol temperature, the built ice thickness was calculated and tabulated for 6.5 hours period at 20 minutes intervals. Thereafter the temperature profile along the ice thickness was tabulated during the end of each 60 minutes (1 hour) up to 6 hours and final data set was tabulated at the end of 6.5 hours. Here the temperature profile was estimated at every 2.5 mm distance along the built ice thickness. The width & length of water filled rectangle enclosure was selected as 10 cm & 110 cm respectively and this unit is called Primary Ice Making Chamber. The height was selected based on the final built ice thickness which was decided based on temperature

of glycol circuit. Finally relevant total energy extracted and final ice volumes were calculated for 3 different glycol circuit temperatures.

In order to achieve the uniform ice thickness inside the Primary Ice Making Chamber, counter flow arrangement was introduced to glycol circuits placed at top & bottom surfaces of it. Still there is a drop of final ice volume. The volume reduction was calculated and relevant total energy removed by the glycol circuit was calculated. This was repeated for 3 different glycol temperatures. The glycol circuits were designed and relevant flow rates were calculated to maintain the heat transfers for 3 designs scenarios. Finally 3 ice thermal storage designs were evaluated. The cost of manufacturing was calculated for all three designs. The operational cost was calculated for all three cases under hotel tariff for using at hotels and under general tariff for using at Movie Theaters. It was revealed that the price of chiller contributes to more than 50% of the cost of manufacturing for all 3 designs.

The payback period for the use case of hotel rooms under hotel tariff was found to be 4.3 years. The use case of Movie Theater has a 3.4 years payback period. This clearly indicates the further possibility of reducing the payback period under both cases used by cutting down the capital cost of chillers. When these units are manufactured on an industrial scale, it would further reduce the cost of chillers by volume discounts. This study makes a clear indication that small scale ice thermal storage systems are economically feasible.

TABLE OF CONTENT

Declaration	ii
Acknowledgement	iii
Abstract	iv
Table of Content	vi
List of Figures	ix
List of Tables	x
List of Abbreviations	xii
List of Appendices	xiv
1. INTRODUCTION	1
1.1 Background	1
1.2 Research Question	2
1.3 Research Objective	2
2. LITRERATURE REVIEW	3
2.1 Concept of cold thermal storage systems	3
2.2 Fundamentals of cold thermal storage and phase change materials (PCM)	4
2.2.1 Sensible heat storage based systems	5
2.2.2 Latent heat storage based systems	6
2.2.3 PCM materials	7
2.3 Operational Basics of Cold Thermal Storage	12
2.3.1 Modes of Operation	12
2.3.2 Operational Strategies & cost benefits of Cold Thermal Storage System	12
2.3.3 Measuring of stored cold thermal capacity	13
2.4 Applications of cold thermal storage systems	16
2.4.1 HVAC Cooling	16
2.4.2 Process Cooling	16
2.4.3 District Cooling Plants	16
2.4.4 Developing Energy Sources - Solar & Wind	16
2.5 Ice Storage Systems	17

2.5.1	Ice Harvesting Systems	17
2.5.2	Ice On Coil Systems	18
2.5.3	Internal Melting	18
2.5.4	External Melting	20
2.5.5	Cost Benefits of Ice Storage Systems	23
2.5.6	Capital cost savings	24
2.5.7	Long term benefits in ice storage systems	25
2.5.8	Encapsulated Phase Change Materials & Ice storage systems	26
2.6	Design Guidelines for Cold Thermal Storage Systems	27
2.6.1	ASHRAE Design guidelines for Cold Thermal Storage Systems	27
2.6.2	How to decide whether Ice Storage or Chilled Water Storage is suitable for a given project.	30
2.6.2.1	Introduction	30
2.6.2.2	Cool storage	30
2.6.2.3	Chilled Water and Ice Storage each offer unique benefits	31
2.7	Mathematical model of ice forming inside a horizontal rectangle chamber with constant temperature at the walls	35
2.8	Prospects of utilization of cool thermal storage for buildings in Sri Lanka	42
3.	RESEARCH APPROACH OF DESIGNING A SMALL SCALE ICE STORAGE BASED AIR CONDITIONING UNIT	45
3.1	Introduction	45
3.2	Design parameters	45
3.3	Design configuration & operational modes	46
3.4	Research methodology	47
3.4.2	Develop 32 Ton Hour capacity 3 ice storage systems based on 3 different glycol temperatures ranges (inlet/outlet) and 6.5 hours charging period.	47
3.4.3	Case 2 & Case 3	62
3.4.4	Chiller operational strategy	62

4. RESULTS & ANALYSIS	70
4.1 Estimating the power consumption of the pump to Circulate glycol	70
4.2 Investigate the manufacturing cost of all three designs	72
4.3 Power consumption of chiller during 6.5 hours charging period	75
4.4 Analysis of results	77
5. Discussion & Conclusion	80
5.1 Conclusion	87
List of References	91
Appendix A : Temperature profile & total energy removal of case 1	
Appendix B : Designing of ice thermal storage based small scale air conditioning unit under case 2	
Appendix C : Designing of ice thermal storage based small scale air conditioning unit under case 3	

LIST OF FIGURES

Fig. 1.1 : Change of typical daily electricity load curve over the years	2
Fig. 2.3.3.1 : Full storage & Partial storage – load leveling	14
Fig. 2.3.3.2 : Partial storage – demand limiting	15
Fig. 2.5.3.1 : Ice thermal storage system design –ice on coil-internal	18
Fig. 2.5.3.2 : Ice storage design –internal melt (indirect contact)	19
Fig. 2.5.3.3 : Ice storage design – internal melt performance	19
Fig. 2.5.3.4 : Ice storage & chiller system schematic	20
Fig. 2.5.4.1 : Ice thermal storage system design – ice on coil – external melt	21
Fig. 2.5.4.2 : Ice storage design – external melt (direct contact)	21
Fig. 2.5.4.3 : Ice storage design – external melt performance	22
Fig. 2.5.4.4 : External melt system schematic	22
Fig. 2.5.8.1 : Phase changing within encapsulated ice balls	26
Fig. 2.5.8.2 : Equipment configuration of encapsulated PCM/Ice storage	27
Fig. 2.7.1 : Forming of ice inside a close enclosure	35
Fig. 3.3.1 : Schematic diagram of ice storage based air conditioning unit	46
Fig. 3.4.2.1: Primary ice built chamber unit	55
Fig. 3.4.2.2 : Composite unit of ice built chamber	55
Fig. 3.4.2.3 : Complete ice storage unit with 12 composite units	56
Fig. 3.4.2.4 : Counter flow arrangement	58
Fig. 3.4.2.5 : Composite ice build chamber unit	59
Fig. 3.4.2.6 : Glycol circuit	59
Fig. 3.4.2.7 : Glycol circuit tube size	59
Fig. 3.4.2.8 : Final dimension of primary ice making chamber unit	59
Fig. 3.4.4.1 :Viscosities of propylene glycol solutions	68
Fig. 3.4.4.2 : Typical glycol flow direction inside the circular pipe circuit	69
Fig. 4.5.1 : Circular glycol circuit with 24 pipes in parallel	85
Fig.4.5.2 : Dimensions of circular glycol pipe	85

LIST OF TABLES

Table 3.3.1 : Operation of valves and fan coil unit	46
Table 3.4.2.1 : Ice build thickness with time –Case 1	47
Table 3.4.2.2 : Ice build thickness with time – Case 1	51
Table 3.4.2.3 : Temperature profile & energy removal in 1 st ,2 nd & 3 rd	52
Table 3.4.2.4 : Temperature profile & energy removal in 4 th ,5 th & 6 th	53
Table 3.4.2.5 : Temperature profile & energy removal in 6.5 th hour	54
Table 3.4.2.6 : Total energy removed during 6.5 hours	55
Table 3.4.2.7 : Energy to be removed by glycol circuit in 6.5 hours	57
Table 3.4.2.8 : Energy balance data	60
Table 3.4.2.9 : Pump flow rate on hourly basis	61
Table 3.4.4.1 : Chiller requirement with & without operational strategy	62
Table 3.4.4.2 : Case 1 - Chiller operational strategy	63
Table 3.4.4.3 : Case 2 - Chiller operational strategy	64
Table 3.4.4.4 : Case 3 – Chiller operational strategy	65
Table 3.4.4.5 : Summary of all 3 cases	67
Table 4.1.1 : Power consumption of the pumps to circulate propylene	70
Table 4.2.1 : Manufacturing cost of case 1	72
Table 4.2.2 : Manufacturing cost of case 2	73
Table 4.2.3 : Manufacturing cost of case 3	74
Table 4.3.1 : Power consumption of chillers for three designs	75
Table 4.3.2 : Customer category H-2	75
Table 4.3.3 : Customer category GP-2	76
Table 4.3.4 : Use case 1 - Hotel room - electricity energy cost per day	76
Table 4.3.5 : Use case 2 - Movie theater – electricity energy cost per day	76
Table 4.4.1 : Use case 1 - Recovery period	77
Table 4.4.2 : Use case 2 - Recovery period	78
Table 4.5.1 : Summary of all 3 cases investigated	82
Table 4.5.2 : Glycol circuit temperature – Case1, Case 2 & Case 3	83
Table 4.5.3 : Achievable ice thickness in 6.5 hours – Case 1, Case 2 &	83

Table 4.5.4 : Rate of energy removal in all three cases	84
Table 4.5.5 : Required Chiller capacity with & without operational	84
Table 4.5.6 : Summary of all 3 cases	86
Table 4.5.7 : Comparison all 3 cases	87
Table 5.1.1 : Power consumption for chillers & pumps during 6.5 hours	87
Table 5.1.2 : Customer category H-2 & GP-2	88
Table 5.1.3 : Energy Cost for operating during off peak time	89
Table 5.1.4 : Recovery period for Hotel Room & Movie Theatre	89

LIST OF ABBREVIATIONS

CTS	Cold Thermal Storage
CEB	Ceylon Electricity Board
GP-2	CEB General purpose tariff for each individual point of supply delivered and metered at 400/230 Volts nominal and where the contract demand exceeds 42 KVA.
ASHRAE	American Society of Heating, Refrigeration and Air Conditioning Engineers
TR	Ton of Refrigeration
Ton Hr	Ton Hours
TES	Thermal Energy Storage
PIMC	Primary Ice Making Chamber
ATES	Aquifer Thermal Energy Storage
CIMC	Composite Ice Making Chamber
M	Mass
P	Density
V	Volume
M	$p * V$
C_p	Specific heat

Nomenclature used for mathematical model

b	Wall of the capsule
c	Specific heat
h	Thickness of the capsule
Hs	Solidification latent heat of ice
k	Thermal conductivity
l	Liquid phase change material
m	Freezing point of water
S	Solidification thickness
Ste	Stephan number
S	Solid phase change material (ice state)
t	Time
T	Temperature
x	Longitudinal coordinate
X	Dimensionless longitudinal coordinate
y	Solidification thickness of ice
α	Thermal diffusivity
θ	Dimensionless temperature
ρ	Density
τ	Dimensionless time

LIST OF APPENDICES

- Appendix A:** The dimensionless temperature ratio quantity Θ_s and temperature of ice T_s along the built Ice thickness
- Appendix B:** Case 2 - Detail designing steps and related tabulated data
- Appendix C:** Case 3 - Detail designing steps and related tabulated data.