INTEGRATED SYSTEM OF BUILDINGS' UPGRADE AND NEW CONSTRUCTIONS[1]

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ABSTRACT

The design solutions presented in this paper are not necessarily new, because a lot of great ideas have been postulated over the recent years, but they are integrated in a compact package that can be used as a blueprint for different climates and different materials. With other words, the design solution is based on building physics. A realization that sustainable, energy efficient buildings require good indoor environment to provide well-being of people and increase their productivity, ensure durability of materials and systems and link moisture management in structures with indoor environment leads us to a new design paradigm for design of new construction as well as for retrofitting of the existing buildings.

In both, cold or hot climates we need to use thermal mass, thermal insulation and airtightness. Yet, we pay a penalty for too much thermal mass and thermal insulation in mixed climates. So undertaking to develop a system for moderating both indoor temperature and humidity that can be applied for both new and existing buildings we need to consider integration of the building enclosure with the heating, cooling and ventilation. If we succeed at this, we will be on the track to a substantial impact in the built environment.

To create a next generation technology such as switchable thermal resistance of opaque walls and switchable thermal mass, manage moisture through use of ventilated cavities that are integrated with HVAC and modify materials to perform a required function we may also have to develop some alterative materials that are designed to fulfil several performance aspects at the same time. When talking about new materials we find that methodology for predicting their field performance is often missing. Thus, to enable development of new technology we must also expand the capability for evaluation of material performance.

KEY WORDS: building physics, building science, learning from the past, history of building physics, system integration, thermal upgrade, thermal rehabilitation, hygrothermal insulations.

1. INTRODUCTION

This paper proposes a comprehensive approach to building envelopes and environmental control systems for mixed system buildings (heavy structure and light, infill walls), with strategies applicable for both new construction and the upgrade of existing buildings towards net-zero and near net-zero energy performance. The climate analyzed in this paper is a mixed heating and cooling climate but one in which cooling performance is particularly critical: for example, the mid-Atlantic region of the United States, South-Central China, or Southern Europe. A review of construction techniques suggests that exterior thermal insulation composite systems (ETICS or

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EIFS) are the system of a choice for cladding for insulating masonry buildings yet such systems present critical limitations with respect to thermal and moisture control on light weight walls. This paper looks at an integrated solution that addresses both the construction of the building and the heating and cooling systems to provide the best environmental quality while reducing energy approaching near energy zero performance.

The strategies discussed here are of particular relevance with respect to climate change, as many temperate regions around the world will see increasing periods of climate. Given that these temperate regions will remain humid climates, it may be argued that building approaches in these climates must do more to address heating, cooling, and moisture control in a single integrated approach, rather than expect a narrow heating season approach to building performance (maximizing thermal resistance, minimizing infiltration) to serve the building all year.

2. THE ENERGY CONUNDRUM

Traditionally, buildings in North America have been conceived with a bias towards heating season performance, with the major performance advances such as thermal insulation, air barriers, thermal glazing focused on energy efficiency in the heating season. These performance advances were or course intended to counter the poor performance of buildings built up until the early 20th century that lacked these provisions.

It is true that in the last decades energy performance in buildings has improved. The average energy use of commercial buildings in 1990 in North America was 315 kWh /m^2. Since 1990, energy use in commercial buildings steadily declined, reaching 250 kWh /m^2 in 2002 (Finch et al, 2010). We could think of this as an improvement, resulting from the latest l advances in building technology.

Yet surprisingly, the energy figures of 2002 are equivalent to those of commercial buildings in 1920. In other words, the masonry buildings using 1920s building technology and building systems consumed as much energy as the shiny, glass-clad buildings we are constructing today, despite all of the energy saving measures we have invested in.

2.1. Masonry Buildings in 1920

Masonry construction technology developed over the course of many centuries, as small improvements to construction efficiency and durability acrued over time. The load bearing function required thick masonry walls and the floors were constructed with masonry blocks, steel and cement, giving the building a huge thermal capacity. As a result these buildings responded very slowly to the exterior climate, leveling out diurnal (day-night) shifts in temperature and thus tempering the building's interior climate against extremes of hot and cold occuring outside. In temperate climates such as North America, these masonry buildings were relatively comfortable without air conditioning by employing simple provisions such as high ceilings, fans, and basic natural ventilation.

The walls in these buildings were airtight because of exterior and interior lime-based plasters. Lime develops strength slowly, allowing settlement of walls while maintaining adhesion and continuity while resisting cracking. Additionally, the plaster and masonry wall was serviceable and could be easily repaired by repointing and replastering if the wall assembly failed. Double-hung windows were well-integrated into the masonry walls and were heavy and sealed with oil paint; although not perfect at resisting infiltration, window area was small in masonry buildings and the windows' thermal impact, mainly radiative heat exchange and air leakage, was mitigated by the rest of the wall system.

Because of the slow thermal response of these buildings to exterior climate and to the building's active heating systems, these massive masonry buildings were often locally over-heated and the indoor temperature would vary between periods of comfort and discomfort as the exterior conditions changed. Thermal zoning was simple, with devices such as radiators controlled simultaneously by users and by a supply of heat (typically from boilres). The large thermal mass tempered the exterior temperature swings, requiring less heat to maintain comfort than in a lighter building that would be more quickly impacted by exterior conditions.

2.2. Building Physics: explaining the deficiencies of construction

What followed in the middle of the 20th century was the development of a multitude of materials and methods that made construction more efficient and having better thermal resistance. Among these new developments were gypsum wall board, plywood, particle board, and fibrous insulation. Furthermore, advances in fireproofing and engineering wood structures made lightweight building preferable.

Coincidentally, introduction of thermal insulation and more moisture sensitive construction materials contributed to appearance of moisture problems. Previously, moisture was not a serious consideration because masonry is resilient to moisture (unless exposed to freezing and thawing). Much like its behavior as a thermal flywheel, the masonry wall could absorb and expel moisture slowly and thus temper large changes in moisture that were introduced by climate or by people.

Scientific knowledge of moisture preceded the moisture problems introduced by new technology. Scientists knew about diffusion theory and the calculation of condensation as early as 1938 (in English: Rowley et al 1938, 1938a, Babbitt 1939, Hechler et al 1942, Teasdale et al 43, Joy at al 1948. in Russian: Franczuk,1941,1957; Fokin,1954; Uszkow,1951; Luikov,1954). While the scientific understanding of moisture remained within the building physics community, North American buildings were developing growing amount of moisture problems. In 1958 a paper written by Glaser described a method to calculate moisture in layman's terms; while the concept was not entirely novel, Glaser explained in a simple, graphical manner how to calculate condensation. As a result, moisture transport by diffusion became a concept worldwide accepted, building community had a new way of rationalizing the moisture problems.

One wonders why the knowledge of building physics was not used in construction and the only explanation is that building physics has been used in passive way. It reacted to the problems observed in building materials and methods and assisted in understanding the failure before coming with the methods of it re-occurrence. Figure 1 shows the manner in which the traditional building physics operates. If tradition is the only way of defining the failure and since we know that performance cannot be defined without a definition of the failure there is no reason for engineering community to be proactive and use the science.

Figure 1: Traditional circle of progress in building science

Of course this traditional pattern of building physics is not acceptable for us today and later in the text, we will discuss how it can be modified.

2.3 Buildings in 1950 – 2000

As we pointed out, wall lost their thermal mass and two major problems emerged.. As insulation was added to the wall, large area glazing that was also introduced into commercial buildings resulted in challenging air leakage problems. While the opaque parts of the building envelope offered improved insulation, the large windows, in turn, created more comfort issues for occupants. The new envelope also lacked the mass of the old envelope, and couldn't offer the tempering effects of the former uninsulated, massive system.

The second problem, closely related to the first was that a light weight building relying on thermal resistance responds to thermal and moisture changes more rapidly. This is in addition to the comfort issues related to glazing. These modern buildings required better environmental controls and the technology evolved to provide full, centralized, forced-air HVAC systems. These HVAC systems could also provide summertime cooling and dehumidification, as well as wintertime humidification. Thermostatic controls for these systems operated with very tight set points – the same for the whole season in summer and winter. Most importantly, these HVAC systems dealt with the indoor air as the primary system providing occupant comfort.

From philosophy viewpoint, a light weight, fully conditioned building eliminated all the advantages that had existed with the old masonry buildings. The effects of thermal mass are greatly reduced when interior temperature is held constant within a fraction of degree. Without thermal mass, peak HVAC loads increase for both heating and cooling, and both delivery and distribution system size must increase. Another significant problem came with zoning these systems. Lightweight, leaky buildings with large amounts of glass have a multitude of microclimates within them that can make single-point thermostatic controls inadequate. The zones within these systems are also designed based on the assumption that the air is static, whereas in reality buildings are plagued by thermal stratification, multi-zonal air flows, and other patterns that work against the operation of the forced-air systems. Furthermore, the HVAC systems singled out dry air temperature as primary feedback system for environmental control, even though building physics tells us that people react to a complex set of environmental parameters including mean radiant temperature, relative humidity, and air movement.

2.4 Evolving moisture and indoor air quality concerns

Water vapor barriers (retarders) were introduced to many national codes and standards. In 1950's, two Canadian standards dealing with WRB and vapor barriers became mandatory. Vapor barriers were required to have a permeance of less than 0.75 perm (45 ng/Pa m^2 s) on aged product and 1 perm[5] was used in both the US and Canada.

Inclusion of these numbers in the national codes gave architects a false impression that moisture control was adequately addressed. The emphasis on vapor control has received a disproportionate amount of ***attention just because it is easy to calculate***. Some "authorities having jurisdiction" went even further – stating that no condensation was allowed disregarding the consideration if the moisture presence can significantly reduce material performance or may lead to deterioration

Wilson and Novak (1959), who analyzed winter condensation between panes of double windows under typical temperature and humidity conditions, showed that when the neutral pressure plane was at the bottom of the window, the calculated vapor transfer by air leakage was 10 times larger than that gained by diffusion. Recognizing that the total equivalent leakage area[6] was about 6 mm^2 distributed along a 3 meter long window perimeter, one can immediately appreciate that air flow is a more effective carrier of moisture than vapor diffusion[7]. There was widespread publication of these and similar results, (Wilson, 1960; Sasaki and Wilson, 1962 and 1965; Torpe and Graee, 1961; Wilson and Garden, 1965; Garden 1965), highlighting the significance of airflow in carrying moisture. There were also a significant number of publications that stressed the need for control of air leakage (Wilson 1960b, Wilson 1961, Garden 1965, Tamura and Wilson, 1963, 1966, and 1967). Despite this published knowledge, many building practitioners were preoccupied with vapor diffusion alone and ignored air leakage.

The singular trend that brought about the change was the promotion of electric baseboard heating in Canada. Builders were attracted to this form of heating because it eliminated the need for a combustion flue, distributed air heating systems and reduced their first-costs. As electricity was more expensive they increased levels of thermal insulation. Yet, higher humidity conditions prevailed in these well-insulated, electrically heated houses and condensation the second floor in

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[5] One must remember that 1 perm was a unit of water vapor permeance introduced to characterize a well performing but leaky wood frame house built in 1930's.

[6] An opening determined under standard temperature and pressure, used to compare air tightness.

[7] To resolve the issue of condensation inside double windows, air leakage testing was introduced followed by requirements that the resistance to air flow be provided by the inner sash only and the space was vented to the outside (Sasaki and Wilson, 1962 and 1965). Furthermore, the introduction of factory sealed double-glazed units (that included durability testing (Wilson et al 1959, Wilson & Solvason 1962) effectively eliminated the problem.

cold regions (Orr, 1974) or attics (Stricker, 1975), and flat wood-frame roofs: Dickens and Hutcheon (1965), Tamura et al (1974). Surveys by Scanada, (1980, 1982) and Marshall (1983) found that moisture condensation occurred on windows in 5 to 10 percent of houses in all regions but it occurred in 20 to 30 percent for electrically heated houses in Atlantic Canada (Scanada, 1981). The linkage between electrically heated houses and climate was transparent.

Wilson, (1960) and Tamura and Wilson, (1963), Tamura, (1975) showed that two interrelated factors caused the change in the indoor relative humidity: changes in efficiency of natural ventilation, and changes in the position of the neutral pressure plane. This led to new recommendations of airtightness of the ceiling construction and new partition-to-ceiling details as they needed to be significantly increased.

Combustion furnaces operated at a much lower frequency in the flue-less houses with the higher levels of insulation, the chimney was either not working or completely eliminated and the heating system did not drive the air exchange as effectively as it was before. Recognizing that natural ventilation could not be relied on to provide sufficient air exchange, National Building Code (model code in Canada) in 1980 required that all dwellings have a ventilation system capable of providing 0.5 air changes per hour (ach). In 1990, based on experience of the builders and occupants, these ventilation rates were found to result in very dry indoor conditions in winter and this requirement was eventually reduced to 0.3 ach.

To this end the building must be tight and its pressure field well controlled (Lstiburek,1999). The focus in indoor environment, indoor air quality and moisture management (White, 1989) moved from the vapor barriers (Karagiozis and Kumaran, 1993) to controlling air flows (Quirette, 1985, 1986, Ganguli,1986, Lux and Brown 1986). The concept of Air Barriers was introduced and tested (Perrault, 1986, NRC 1988, 1990, Trow 1989, Ortech 1990, MH 1991).

This example also highlight the fragmentation of the design process. Architects and designers i.e., people who deal with design are different from mechanical engineers i.e., people who size the HVAC equipment. While the concept of air infiltration through cracks around windows and doors were well established in Germany in 1960's and introduced to heat loss/gain calculations, its effect was not given much consideration in the design of walls **for the next 40 years until the quest for sustainability resulted in a** change in the design paradigm.

2.5 The need for integrating buildings physics into the construction process

The holistic approach to design that was normal in 1920's is missing today. We are changing today the design paradigm to involve the whole design team already in the conceptual project. It is also time to integrate building physics principles in to the conceptual; design stage and approaching the design of building in a holistic manner, as it was done in 1920s Today, buildings are too complex to be conceived under the authority of one architect; instead buildings are conceived and built by teams representing several interests. To realize performance in the holistic manner described above, the many members of the team must share common knowledge of building physics that allows them to communicate at a critical level in order to define objectives and make decisions. While architects continue to play an integrating role within these teams, it is especially important for architects to understand building physics to an extent that they may communicate with experts regarding these issues.

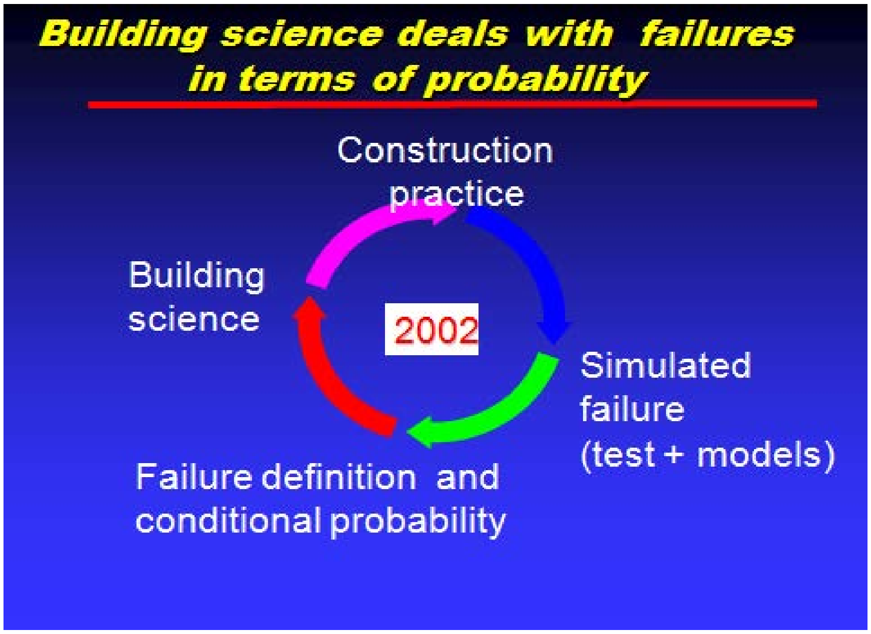


Figure 2 Building science circle based on integrated testing and modeling approach where the simulated failure is derived from hygrothermal modeling

So we need to train young architects to understand building physics to the extent allowing them to listen to a group of experts who design

[A] The energy efficient envelope – needs to be designed understanding both thermal, moisture, and air infiltration issues,

[B] Durable building that has been evaluated for initial and long-term performance as well as maintenance and operation costs

[C] excellent indoor climate.

This architect may like to divide the process of indoor environment control into a few stages:

- Delivering amount of fresh air needed for each designated zone. Note that the medical profession determined this amount more than 100 years ago, yet the engineers argue how well or how poorly we deliver fresh air to people. Instead of specifying the different requirements for the various air delivery systems since their mixing efficiency is not identical, the leaned committee tries to do one estimate for all HVAC systems and change the standard every few years
- Providing local exhausts to contain sources of pollutants but also air distribution systems that mix “old” and “fresh” air during the delivery process and thereby modifying the effect of all sources and sinks of pollutants.
- Balancing ventilation system with individual exhaust (or intake). (Observe that many different options for air mixing and delivery exist, but this is beyond the scope of this paper).

Furthermore, the concept of environmental control of large buildings has also evolved. We now treat a large building as a sum of single zones. These zones must be separated by fire and air barriers in the floor space and each need to be equipped with individual zonal controls.

3. A CALL FOR BETTER TOOLS

Building physics deals with the effects of climate on buildings and since no testing can assess effects of yearly changes in climate on performance of the building enclosures, we must use hygrothermal (HT) modeling.

In 1971-4 different hygrothermal models were developed at Lund University in Sweden and their comparison showed that if we measure material characteristics properly and we can use different description of moisture potentials to obtain the same results. Furthermore, one of the models included approximation of the capillary hysteresis. Today, we have over 40 published hygrothermal models used for parametric analysis but none of them is suitable for real time calculation because none of them deals with the capillary hysteresis. On the side of energy calculations despite of many research papers (Tamura and Wilson, 1963, 1966, 1967, Tamura et al 1974, 1975, Said 1997, Kosny et al 2007, Lstiburek, 1999, Lstiburek et al 2000, 2002, Vijseundera,1996; Bomberg and Thorsell, 2008; Thorsell and Bomberg 2008, 2011) not a single energy model includes effects of air and moisture transfer through walls.

Why is the progress in modeling so limited? Well, because designers and architects do not use hygrothermal modeling for real time calculations that could allow making decision for practice. And why architects do not use the models? Well because they are not developed for real time calculations. Typical story: what was first an egg to hatch the chicken or chicken to lay the egg.

Building physics does not have any impact on construction industry. We gave examples of many papers and books published before Glaser (1958) published the method that can determine whether condensation will take place at given outdoor temperature and relative humidity of indoor air, ***but it cannot establish the amount of condensation***. There are a few reasons why calculation of the amount of condensation using this method is physically incorrect:

- The presence of condensed water affects the rate of moisture transport by modifying the quasi-steady state assumed in these calculations.
- Condensed water can evaporate and continue the diffusion process until reaching a significant change in the resistance to vapor flow
- Condensed water can move in the liquid phase by osmotic, capillary or other forces.

In other words, this tool tells us when more careful consideration of the design is needed but is not suitable for making all decisions concerning the design of walls.

So, let us be clear: **we do not have adequate analytical tools**, *our energy models do not include effect of air and moisture flows on building energy, our hygrothermal models cannot predict interim effects of wetting and drying* and our codes and standards are related to prescriptive thinking of the past – yet, we must be able to innovate and evaluate performance of the new approaches. In this context, the 2014 industrial initiative “Outcome-Based Pathway” that expands the *Moving Forward* report of the National Institute of Building Science[8] submitted to the President of the United States in 2010 and was focused specifically on the actual energy used in the building states:

> "The building community needs a better baseline of actual building performance against which to measure progress. More importantly, the application and use of prescriptive criteria must be eliminated in favor of stated performance goals or expected outcomes (although, after setting those goals or outcomes, prescriptive guidance to achieve them can be developed).
>
> The industry group specifically focused on an outcome-based approach to address a number of challenges facing the building industry:

- Code departments have limited resources available to enforce building codes (particularly energy codes, which are not usually seen as a life safety issue).
- Energy use is highly measurable, yet current code pathways anticipate results from designs; they do not assess actual building performance.
- Designers do not have the flexibility to use some of the latest technologies or practices to achieve energy efficiency requirements.
- Not all energy-saving strategies, such as building orientation, are effectively captured in codes.
- Energy efficiency goals increasingly rely on reductions in energy use at the systems level, but the IECC has primarily focused on a component approach.
- A growing percentage of energy uses associated with buildings are not currently covered within the existing code framework (i.e., plug loads).

This evolution to outcome-based performance requirements recognizes that prescriptive and modeled design approaches are often not representative of the actual energy outcomes of buildings and that current codes fail to regulate some of the most significant energy end uses in buildings today". While energy use can easily be measured and therefore the change was easy, yet the stress on measurable performance as opposed to using models is a significant development in the USA.

Summarizing this review we found that there is no problem on the innovation and creativity side of technology. There is no problem with the society good will, in all developed and developing countries standards and codes are writing more and more stringent requirements for energy efficiency and 'green' actions.

So where is the problem? The definition of the problem was given by Marshall McLuhan when talking about the communication:

Our Age of Anxiety is, in great part,
The result of trying to do today's jobs
With yesterday's tools

[8] The U.S. Congress established the Institute to serve as an authoritative source in regards to performance criteria, standards and other technical provisions, and we are proud to be able to bring together industry leaders to introduce a means to streamline compliance with codes said the NIBS president.

Energy modeling so far, has been preoccupied with mechanical devices only neglecting the interaction with building enclosures. To produce correct results, any hygrothermal or energy model must include information on air leakage trough the walls and estimate effect of air and moisture transport on energy. This is particularly important when we intend to develop walls acting as heat and moisture exchangers. To introduce the proposed new technology we need to improve the current hygrothermal models that are developed for parametric study to the real time modeling of the interacting transport phenomena.

The extrapolation of hygrothermal modeling capability is necessary because the hygrothermal insulation offers both significant economic advantages through the reduction peak energy loads (Simonson et al, 2004, 2004a and 2005) as well as by modulating indoor relative humidity. The indoor humidity affects both indoor air quality and durability of the building construction.

While we need to improve our tools we also need to look beyond what they can do and design the with a clear performance outcome. The tools can only help us to finetune the desired outcome.

4. THE UNIVERSAL WALL

Most of the building physicists agree that a universal wall should include the following layers, starting from the outside:

1. Rain screen (that does not need to be tight as long as the air gap behind it has an air pressure close to the exterior),
2. Water resistive barrier on the exterior side of the continuous thermal insulation layer
3. Load bearing structure in form of continuous masonry or frame wall
4. Interior trim and finish that includes washable, fire protective layer.

In cold and moist climates the brick veneer has the best reputation even though it may only claim to be only pressure moderating (partly equalizing) rain screen. Yet, it has a drainage and significant moisture storage capability. Effectively the air gap may not be ventilated if one can provide a system with water absorption and drainage. For instance, one can use drainable insulation with extra protection on the bottom 200 mm (drainable insulation that normally does not drain on the bottom strip). Of course, one needs to ensure that the inner wall (the structural part of the wall) is airtight so that air flow can carry the rain water inward.

4.1. Another option of the Universal Wall

We can modify requirements of Johansson (1947, and introduce Water Resistive Barrier (WRB) on the continuous thermal insulation and air barrier (AB) located preferably next to the insulation. So this universal wall includes

1. Cladding (that may be leaky)
2. Water Resistive Barrier that controls water ingress and to some extent also controls the water vapor diffusion in both directions. WV flow inwards caused by thermal drive (from sun radiation) and outwards called by thermal gradient in cold season
3. Continuous layer of exterior thermal insulation
4. Air Barrier system that controls flow of air between the wall and environment on each side of the wall (this description implies that air may also flow within the wall)

5. Load bearing structure in form of continuous masonry wall or infill walls in the structural frame
6. Interior trim and finish that includes washable, fire protective layer that also needs to control ingress of air and water vapor into the wall.

The price that we pay for eliminating the vented air gap that would enhance drying of the walls in cold climate, is the need to introduce moisture control on both sides of the wall. Both air and moisture flows are now considered on each side of the wall. Of course the degree of moisture control varies with climates.

The next question is how much insulation can we place on the outside of the walls and how much is needed to place in the interior of the wall if we design NZEB?

In our opinion, on masonry walls we can place up to 100 mm of thermal insulation with density about 20 kg/m^3 or 75 mm of heavier insulation with density about 30 kg/m^3 when we use Exterior Thermal Insulation Composite System (ETICS or EIFS) with the synthetic plasters that typically have the lamina weight about 6 - 8 kg/m^2[9]. We have long experience indicating that masonry walls have adequate stiffness and that long mechanical fasteners work well

We may have not have enough data to specify limits for wood and steel frame walls, but putting the limit of 75 mm for the elastic, low density foams and 50 mm for stiffer and heavier foams appears to be within the reason. Since, except for the extreme cold climate, some thermal insulation is always placed inside the cavity of the fame walls, we may recommend for all types of walls to add on the interior side 50 to 100 mm of traditional insulation with performance identical to the exterior insulation (i.e. Rsi 2.65 or R15 imperial). Of course, one typically recommends more for the super insulated or “passive houses” but **our thesis is that more than Rsi 5.3 is not necessary** if one uses a fully balanced approach to design of NZEB.

Yet, there are situations e.g. in historic buildings where exterior façade need to be preserved and the full thermal upgrade must be done on the interior. There also mixed climates in which, as we postulated by Bomberg (2010) we need to use switchable thermal mass and switchable thermal insulation and we may want to place more effective thermal performance on the interior side.

4.2. Environmental controls

The traditional development used air for control of indoor environment with central air systems air conditioning units or air to air heat pumps. Yet, this air as the carrier is much less effective than the surface heating and cooling offered by hydronic systems. We propose to use them in the form of prefabricated panels for floors or partition walls.

From building physics point of view we need to connect mass with indoor climate and this is why the natural place for cooling or heating heat exchangeres is on the components with thermal mass.

[9] If mineral fiber is used instead the foam insulation, because of the unknown long-term cohesive and shear strength of the mineral fiber boards the whole force must be carried by the mechanical fasteners connecting masonry substrate with the reinforcing mesh of the lamina. We cannot comment on how far this approach would be acceptable for frame wall systems where movements are larger.

5. INTEGRATION IN DESIGN AND CONSTRUCTION

As Steven Covey wrote in the book entitled Seven Habits of the Most Effective People: ”start with the end in mind”. The current situation in construction industry reminds us the time when Canada had two leading politicians; one said: “hurry up, the buss is waiting and while we drive we will decide where we want to go” and other said: “hurry up, the buss is waiting, so before getting into the buss, we must sit and think where we want to go”.

In the industrial context, however, we must deal with the both conflicting approaches at the same time – some people continually improving their products and other people thinking how to achieve the same goal without using the current products.

To proceed with this discussion we assume that we deal with a multi-unit, uninsulated masonry, apartment building located in predominantly cooling climate to be upgraded to NZEB level.

5.1. HVAC Integration

For heating and cooling we will select water to water heat pump (or a split HP with water system used for cooling) and independent ventilation system. As we deal with a rehabilitation the heating/ cooling panels will be placed on two interior walls. Solar panels are also added to the existing walls and they will provide more energy thermal in winter because of the low angle of sun. This energy is partly used for domestic hot water, and partly for the hot terminal of the HP.

5.2. Ventilation, Humidity, and Moisture Control

For ventilation we will use a central air intake, provided with HEPA filter and dehumidifying device in summer (or humidifying devices in winter, if so is needed) and a small diameter, high velocity, flexible ducting. In cold climate, ventilation air will be delivered near the floor, in coolig climate near the ceiling on the same wall where the apartment entry door is located. The exhaust of the air is near the floor level on the exterior wall that functions as the heat exchanger. The air drawn from the room is led through a cavity created in the insulation to the small ventilator placed above the window. The ventilator is operated either by a CO_2 sensor located in the room or by a remote control used for the night ventilation period.

The reason for this system is the need to control the quality of the fresh air delivery. The central air intake for ventilation can easily ensure cleaning air from pollutants, dust and removal of humidity excess. This dehumidification is needed to improve the human comfort during the high air temperatures without feeling of the “stuffiness “of the air and separation of dehumidification from cooling is economically justified. This is all that needs to be done on the central air intake. The other elements of indoor environment will be addressed with smaller clusters of one or a few dwellings together, as it is most efficient.

One of the critical components of indoor environment is the human aspects of the indoor air quality. For centuries, we opened windows as the means of individual climate control. Yet often the outdoor air that is too hot or too cold, too humid, etc. On the other hand, we know that for any ventilation system to be effective it must be balanced i.e. neither driven by the supply nor by the exhaust. So, the solution is simple. We deliver fresh, clean and dehumidified air from central air supply with a slight overpressure (say 4 Pascal) to each apartment in the building but we exhaust it locally with provision of individual controls.

In this approach the buildings are designed with small overpressure and the individual ventilation in each dwelling is designed to allow people to improve the quality of air by exhausting air as if they opened window, except that incoming air is purified and air conditioned.

5.3. Maximizing effects of thermal mass

We are proposing a different pattern of thinking, one that offers substantial potential for economic trade-offs. Almost complete elimination of thermal bridges that is some AAC structures may be as high as 40% (Kisilewicz, 1999) but we count it only as 15% (Vinieratoes and Verschoor,1980; Petrie et al 2000). Next 15% comes from the elimination of peak loads in heating or cooling (Simonson et al, 2004 and 2005). Adding 10 – 15% for using airtight construction and integration of radiant water heating with domestic hot water (Brennan at al, 2008; Wallburger et al, 2010) as well 10 to 18% for the night ventilation in hot and humid climates, we are starting with more than 50% reduction of loads before we add the reduction coming from the integration of low energy sources that we currently cannot estimate.

5.4. Ventilated Wall Cavities for Interior and Exterior Wall Construction

Figure 3 shows temperature profile vs thermal resistance of the wall in summer for a wall without ventilated cavity (dashed line) and wall with conditioned air flowing in the cavity (solid line).

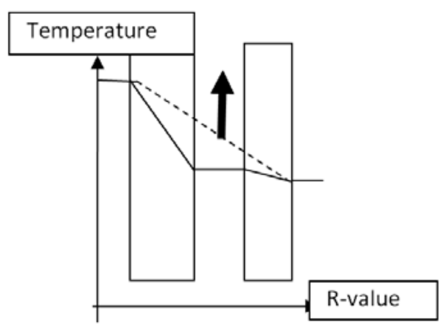


Figure 3: Temperature distribution in the wall ventilated with preconditioned air in summer conditions vs one with sealed non-convective cavity

One may see that if the air has different temperature, the values of incoming and outgoing heat flux are different.

Studies on dynamic walls in CRIR, France in 1980's, showed that the difference between static and dynamic performance of the wall is small; yet, the latter permits much better control of air flows. Furthermore, when one uses different sources of energy one can increase the use of low exergy (low grade energy) and reduce the use of high quality energy.

The most important aspect of the ventilated air gap technology is, however, the capability to close or open air flows as needed to switch on or off the effects of thermal mass and thermal resistance. In mixed climate use of heavy mass and high level of thermal insulation often results in energy penalty when indoor environment is too slow to follow the changes in the outdoor temperature.

Using the whole wall as a heat exchanger (Bomberg 2010) not only eliminates the use of hear recovery ventilators (HRV) but also permits individual ventilation of each room. Furthermore, it also enables integration with the solar thermal collectors that can be used for domestic hot water system. Using water to water heat pump with two water tanks (that can be integrated with hydronic heating/cooling system) one can also use wall solar thermal collectors in winter in the cold climate regions as glazed or an unglazed construction. A thesis work in central NY showed that with highly efficient insulation system the solar gains can be of significant input to the energy efficiency of the whole system.

Comparing the experience of ETICS on masonry with that on wood/ steel frame walls we came to the conclusion that the North American failures are more associated with the movements and flexibility of the substrate than the ETIC system itself. To avoid such problems we decided to include both structural and environmental considerations in design of the panels. The panels will include fire protection board, hygrothermal insulation and vented or ventilated air spaces for controlling moisture in the wall assemblies. In their design, sufficient stiffness for wind loads and durability in freeze-thaw environment will be critical considerations.

The experience shows that there will be a fundamental split between the masonry walls where ETICS will remain the fundamental approach for continuous exterior thermal insulation systems and frame walls where a new panel system needs to be developed. For the masonry walls the connection between the indoor environment and the interior thermal insulating panels will be integration of the ventilation system. To this end we propose:

1) The function of integration with HVAC will be moved to the interior panels
2) Interior panels may include additional interior thermal insulation and ventilated air cavity
3) The interior insulation may also be a hygrothermal i.e., may include moisture buffer function and may also have PCM encapsulated at the inner surface of panel thereby providing additional means of indoor temperature control

Yet, we do not have suitable materials for moisture buffer. Gypsum sheets are too heavy for the interior applications and not sufficiently water resistant for the exterior applications – so the is a need for a new composite materials.

5.5. Hygrothermal Insulation

Development of capillary active layers to prevent mold growth and reduce heat loss (Haeupl et. al., 1999, 2002) opened the door to using interior thermal insulation as a viable component of thermal upgrade for historic building where the existing façade needs to be preserved. With the rapid growth of hygrothermal insulation and much improved capability of moisture management (based on hygrothermal models) the coupling between ventilation and blending of different energy sources became possible on either side of the wall exterior or interior.

Iin this paper we are not discussing the exterior side of the wall. For interior hygrothermal upgrade of exterior walls we select interior panel system that is applicable to all types of walls (masonry, concrete panels, steel or wood frame).

Figure 4 presents the concept of capillary active insulation, as introduced by Haeupl (1999, 2002). The layer placed on the interior side of the masonry wall should have high capillarity to redistribute moisture condensed on the back side of the thermal insulation allowing it drying back

to the indoor air. In this way the capillary active layer can perform both the function of thermal and moisture protection.
One can ask the question why does the capillary active insulation must be open for diffusion? To answer this question we need to go back to the principles of moisture transfer in capillary porous materials. Figures 5 and 6 show a technique developed by Bomberg and Shirtliffe (1978) that uses a wet specimen that is sealed in a polyethylene bag and placed in a heat flow meter apparatus to be exposed to the specified thermal gradient.

Thermal gradient drives moisture in vapor phase toward the cold side. This process goes fast in the glass fiber insulation (Figure 6a), and moisture is carried to cold plate of the equipment already in 3 to 4 h and the final dynamic equilibrium develops in the span of 9 to 10 h. The process of redistribution goes much slower in the cellulose fiber insulation (Figure 6b). At the period 3 to 4 h a significant fraction of moisture is still on the warm side of the specimen and the final dynamic equilibrium develops in the period of 17 to 18 h. We use term "dynamic equilibrium" because it is a combination of two conflicting transport processes.

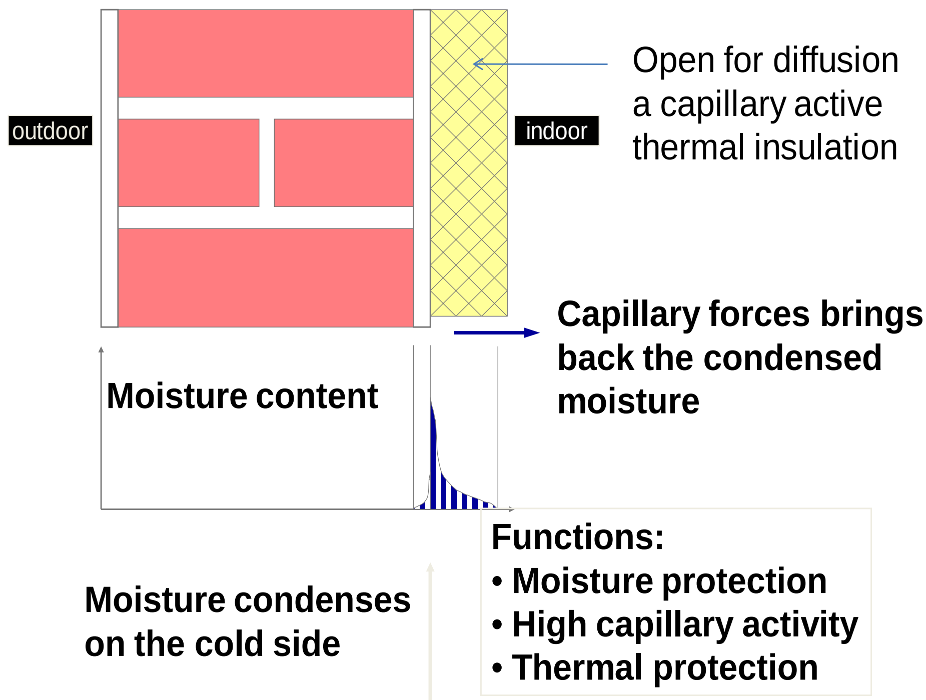


Figure 4: Principles of the capillary active insulation (Haeupl,1999, 2002)

Water vapor is driven toward the cold side and condensing there comes to a very high level of relative humidity at which liquid flow develops. As liquid viscosity is not strongly depended on temperature, the liquid flow tries to equalize moisture content i.e., drives moisture backward. How far backward it can be pushed depends on amount of moisture and liquid flow component in the total moisture conductivity expressed as a function of moisture content.

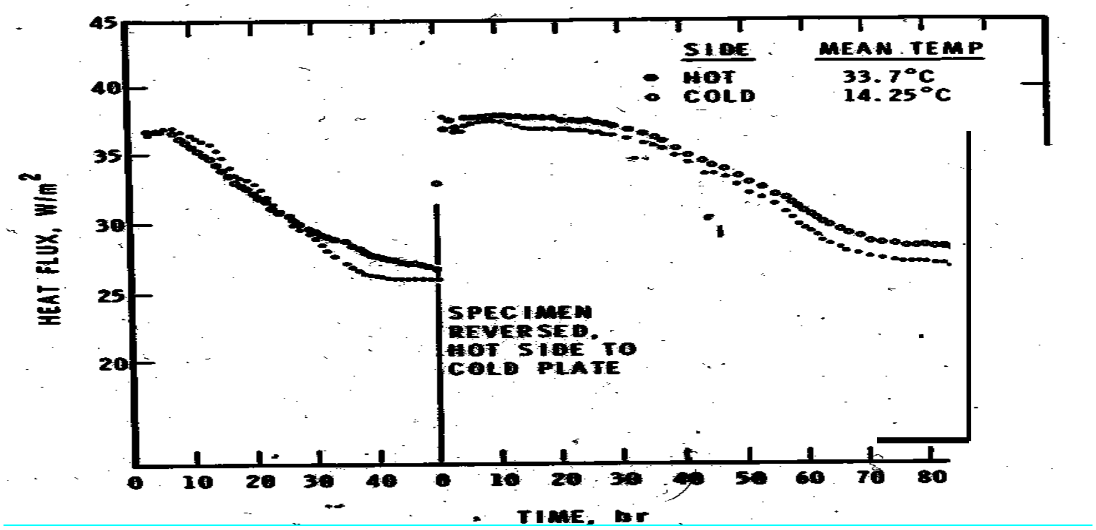
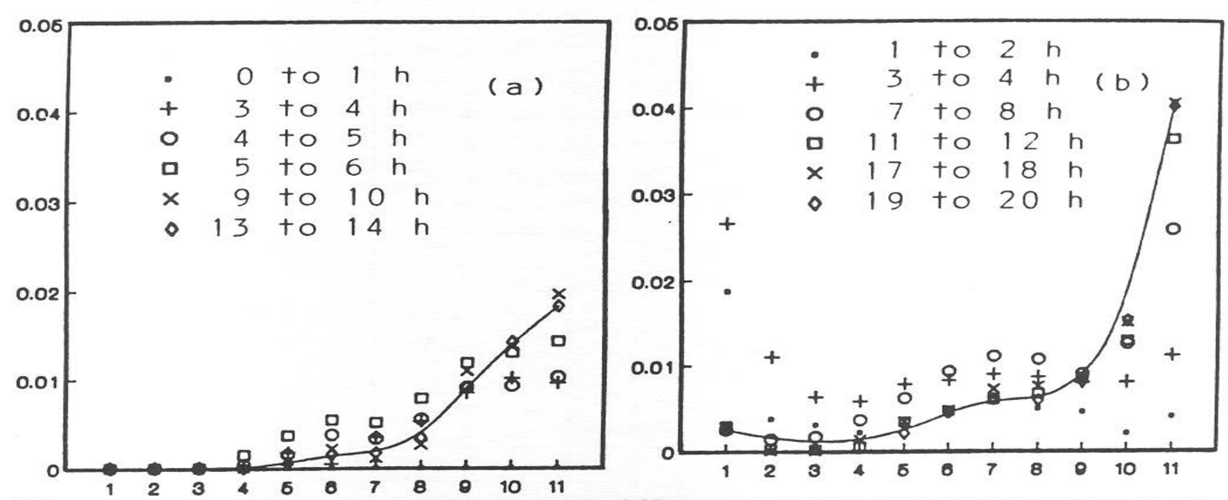


Figure 5: Effect of thermal gradient reversal in a sealed specimen on the heat flux incoming and outgoing from the specimen (Bomberg and Shirtliffe, 1978)

Figure 6 shows moisture content redistribution in the same type of experiment performed by Kumaran on the glass fiber and sprayed cellulose fiber specimens.



(a) (b)

Figure 6: Moisture content redistribution in a sealed specimen. (a) Glass fiber; (b) sprayed cellulose fiber (from Kumaran,1989)

The technique shown in Figure 6 is one of the most powerful tools used for verification of material characteristics used as input data to hygrothermal models (Bomberg and Pazera, 2010). It can also be used to assessment of the hygrothermal properties used for capillary active materials. Figure 5 shows, however, why a high water vapor permeance is required for a good candidate of capillary active material. The residual moisture content on the warm side of cellulose fiber is high and this material can dry inwards even though the bulk of moisture is transported to the cold side.

The concept of capillary active insulations was applied to thermal rehabilitation of masonry buildings. The critical consideration was the elimination of mold. After successful demonstration for several German buildings, this technique was also used in a few world known monuments such as the church of Our Lady in Dresden, some cultural properties in Japan and Rijksmuseum (Rembrandt) in Amsterdam.

The concepts used in capillary active layers are now expanded to include hygroscopic buffer materials that in combination with the capillary active materials allow on use of moisture as a phase changing material and therefore we have introduced a term of "hygrothermal insulation".

6. FUTURE WORK

In designing for environmental control, professionals integrate two very different conceptual processes. One involves specific testing and analysis; the other encompasses broad qualitative assessments based on experience, judgement and knowledge of what makes a building envelope function. On the analytical side is a complex array of tools, models and data which describe the material, structural and environmental factors relating to the building envelope. On the qualitative side there is a sense of how a particular building enclosure would function.

At the moment, we do not have hygrothermal models suitable for real time designing walls with ventilated cavities undergoing repeated cycles of climatic changes. Most of the modeling effort is dedicated to energy models, yet those models are also simplified and do not consider effects of air and moisture transfer on building enclosures.

Effectively, parallel with the need for significant improvements of the hygrothermal models we need to undertake experimental research and demonstration projects to verify the integrated concept proposed in this paper. Such experimental work must include at least two components:

1. Developing guidelines on "Adding interior insulation while avoiding interior condensation". Yet, as we realize that enclosing the sealed space without any venting may lead to creating a source of odours, so the next layer of insulation must be added with a vented air space between them. The solutions should be first established with a computer modeling and later are verified on the full scale building.
2. Developing guidelines on a ventilated air space with an entry at the floor level (behind a floor molding) and with the exhaust at the top sill of the window frame we make the exterior wall function as a heat exchanger for both heating and cooling. Since a slow movement of air is required for this heat exchanger, the air space is typically created by channels made during production of the foam insulation. Note that the position of this ventilated air space is always in such place that the winter condensation is eliminated.

The parallel work on hygrothermal modeling and full scale testing of new concepts is necessary to reach the full integration of building enclosures and mechanical systems.

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