STRUCTURE AND ITS ENCLOSURE

The Condensation Paradigm: an obstacle to housing technology innovation

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Origins of the condensation paradigm

Early origins

The condensation paradigm is the mode of hygrothermal analysis of building envelopes characterized by three assumptions:

- Indoor or outdoor vapor pressure under extreme conditions represents the design load
- Steady state analysis using diffusion, thermal conductance and vapor permeance is the design tool, and
- Condensation prevention is the principal performance criterion.

Most of the current regulations regarding moisture control in buildings are predicated on the condensation paradigm.

The paradigm arose in the 1930s in response to the finding that insulated frame buildings showed widespread paint peeling. Researchers at the Forest Products Laboratory called attention to this problem, especially Brown[1] and Teesdale[2]. Its resolution fell to the young fiberglass insulation industry, and in particular to the Director of Technical Publications of Owens-Corning Fiberglass, the architect Tyler Stewart Rogers. In 1952, Rogers described his efforts of 1937 and 1938:

Condensation has occurred in buildings from the earliest days of man's shelter. I am sure the cave dwellers complained of it. In recent years it has come into prominence, not because of its newness, but for several other reasons: One of these is that we should no longer tolerate the annoyances and destructive action of unwanted moisture. We have advanced so far in building design that imperfections of this character simply must be eliminated. Another reason is that with new materials and techniques and design we have new things to blame for the faults in our buildings. It is never in fashion to blame ourselves, of course; it is always some other Joe who caused the trouble. So paint failures were at first blamed on insulation until the insulation industry, in self defense, had to undertake research to establish its innocence.[3]

Note that the efforts described here were done to protect (in effect, to indemnify) the insulation industry in case of claims of damage that might occur in insulated buildings. Rogers went on:

While this research and similar work by the paint industry was going on, there was a great deal of buck-passing. The insulation men blamed the paints or the wet lumber and some painters retaliated by refusing to paint an insulated house. Then the building paper manufacturers got caught in the middle; their new sheathing papers were blamed for causing condensation instead of shielding a building from dampness. The foils were soon in the ring with the papers, while architects, builders, building owners and the general public watched this battle royal and wondered if any of the fighters was worth betting on.[4]

The research Rogers described, funded through the National Mineral Wool Association, was conducted by Frank Rowley, Professor of Mechanical Engineering at the University of Minnesota. Rowley had been measuring the thermal resistance of building materials through the 1930s, and this work led him to renown within ASHVE (American Society of Heating and Ventilating Engineers); he was president of the society in 1934. When the insulation industry was faced with damage claims arising out of the use of their products, they turned naturally to Prof. Rowley. Rowley developed both a theory and a testing campaign at the behest of the mineral wool industry. The theory was diffusion through solid materials.[5] The reason Rowley selected this mode of moisture movement was expressed in the first paragraph:

For convenience it has often been assumed that the laws for vapor transmission are similar in form to those governing the flow of *heat through the walls of a building, and that coefficients of vapor transmittance may be developed for materials or combinations of materials which may be applied in the same manner as coefficients of heat transmission. In making this analogy it is assumed that the difference in vapor pressures between two parts of a structure is the motive force which causes the flow of vapor...*[6]

In other words, the diffusion theory was selected as the explanatory mechanism not because it was validated or shown to explain the observations, but because it was analogous to conductive heat flow, with which Rowley was most familiar. See Figure 1, an illustration of the profile method used to predict diffusion flow. Rowley also undertook a campaign to measure condensation on plates of aluminum placed in the cavities of wall and roof assemblies, and subject to artificial cooling in a climate chamber.[7]

Rogers jumped the gun, however. He published his article "Preventing condensation in insulated structures"[8] in the March 1938 *Architecture Record*, predating the appearance of any of Rowley's research by several months. The article is striking in several regards. It was the first such article in the building industry literature, and many writings today adopt the same concepts, conventions, wordings and diagrams that were contained in that first article. Also, it exhibited considerable graphic appeal—normal, given the architecture background of its author. It also makes clear at the outset the importance the author attaches to protection of his industry: "Architects, owners and research technicians have observed, in recent years, a small but growing number of buildings in which dampness or frost has developed in walls, roofs or attic spaces. Most of these were insulated houses, a few were winter air-conditioned. The erroneous impression has spread that insulation "draws" water into the walls and roofs."[9] In fact, the use of insulation does lead to elevated moisture content in exterior cladding and sheathing, but that is the subject of another paper.[10]

This *Architecture Record* article created the impression that under the diffusion theory, water found in exterior sheathing and cladding originates at the interior of the building during cold weather. The theory in fact proves the contrary—the water in exterior materials comes primarily from the ambient air surrounding cold materials, not because those materials are enclosing a building with indoor humidity. However this impression served the more general purpose of deflecting concern away from the insulation itself, and toward occupants' indoor humidity production (blaming the victim), as well as toward those who would be expected to carry out the unfamiliar practices, recommended in the article, of vapor barriers and attic ventilation. The article was accompanied by Time Saver Standards no. 101 "How to find Heat Transmission in Building Sections" and no. 102 "Preventing condensation in insulated structures."

Later applications

At the time of the origins of the condensation paradigm, 1938-1939, the groundwork for future efforts at moisture control in buildings was laid. An extended discussion of the consequences of these origins is in preparation. That discussion will include:

- The appearance of the first quantified regulations for vapor barriers and attic ventilation in January 1942 by FHA, predicated solely on Rowley's research
- Britton's research in the later 1940s, with data that ran contrary to the theory, but recommendations consistent with the theory,
- The rejection of the diffusion theory by Canadian researchers and their focus on air movement,

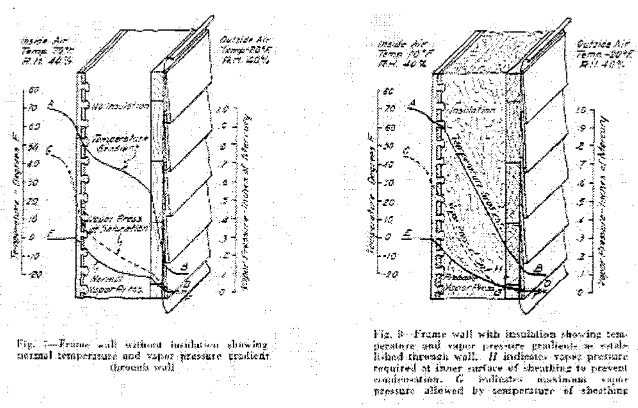

Fig. 1. Illustration of the wall profile method using vapor pressure calculations. This method lies at the heart of the condensation

- The emergence of US model building codes and their adoption of the recommendations promulgated graphically by Rogers and quantified by FHA
- The adoption of the diffusion paradigm by Ramsey & Sleeper *Architectural Graphic Standards,* Fourth edition.
- The "War against Water" campaign by the National Paint and Varnish Association[11], which used McCarthy-era paranoia to market vapor barriers, reduced indoor humidity, and paints. See Figure 2, a pamphlet cover from that era.
- The "Condensation Conference" of the Building Research Advisory Board[12] which summarized the state-of-the-art in February 1952, and provided expectation that guidelines would change in a year or less.

Critical view of the condensation paradigm

Condensation is a concept from elementary physics: it is the change of phase of any material from vapor to liquid state. The experience of condensation on glass and metal surfaces is well known. But as well known as the definition and experience of condensation are, the application of the term "condensation" to moisture effects in building envelopes is very troublesome.

Unlikelihood of condensation occurrence

Two meanings are typically given to the term "condensation": 1) the physical and phenomenological meaning apparent as window condensation—the appearance of droplets associated with phase change, and 2) crossing of the vapor pressure and saturation vapor pressure (svp) lines on a profile chart. This analysis is described in ASHRAE Handbook of Fundamentals 2001 Chapter 23.

Condensation never (or almost never) occurs on most building materials—those that are porous and hygroscopic. Water binds chemically and mechanically to sites in the structure of materials such as wood, gypsum, brick and limestone. "Bound water" is not in the pure liquid or vapor state, and the amount of energy needed to create exchange between bound water and vapor is quite different from the energy needed to produce evaporation or physical condensation. Bound water tends to distribute itself smoothly or uniformly through the materials following rules quite different from Rowley's. Porous and hygroscopic materials would have to be saturated before their surfaces begin to exhibit the phenomenon of condensation. Rather, they store moisture and their moisture contents (and moisture distribution) vary naturally as functions of temperature and humidity changes around the materials.

Low flow rates under diffusion

For another thing, diffusion is an incredibly tiny means of vapor transport. Early efforts at quantification in the US saw the adoption of the term "perm" to refer to units of mass flow of one grain (1/7000 of a pound) per hour-square foot-inch of mercury vapor pressure. With metrication, the units become nanograms (10^{-9} grams per second-square meter-Pascal of vapor pressure). Note how minuscule the mass quantities are. It is fair to ask if damage can occur under flows so slow. While damage has been demonstrated in laboratory and field laboratory conditions, an informal telephone survey of several building scientists by the author indicates that, quite possibly, moisture problems due to moisture diffusion from simple indoor and outdoor vapor pressures have never occurred in the field.

Appropriateness of loads for analysis

For another, the notion that indoor or outdoor water vapor is the design moisture load on buildings has come under much fire. Most building investigations show that, where water problems occur in buildings, they make patterns of sharp gradients with a strong gravity component. In other words, most water problems are due to rain leaks through roofs; rain leaks around windows and in wall details, seepage through foundations, plumbing defects, and floods. The other prominent means of moisture deposition leading to damage are moisture-laden airflow under mechanical or buoyancy conditions, and solar-driven diffusion in assemblies with high moisture-storage claddings.

Appropriateness of use as a judgment criterion

Perhaps most importantly, "condensation" in building envelope assemblies is not an appropriate criterion to distinguish acceptable from unacceptable building envelope assemblies. Its occurrence is practically impossible on normal porous building materials. Misuse of the profile analysis method leads to widespread overprediction of "condensation". The physical conditions for mold growth[13] is a much better criterion to use in distinguishing acceptable from unacceptable building envelope assemblies. Mold would drown in the presence of actual saturated condensation.

More appropriate hygrothermal analysis accounts for moisture storage, latent effects, capillary water movement and, most importantly, the surface conditions creating the potential for mold growth. Several computer programs are designed to perform these calculations.[14] Those approaches will not be discussed here.

Impacts

How does the condensation paradigm affect our ability to deliver housing using innovative technology? We can review three impediments that the condensation paradigm offers.

1. Chilling innovation

Innovative technology is often discredited on a basis of testimony or fear arising from the condensation paradigm. Below are four examples that illustrate conflict between anticipated performance based on theory and actual performance. Space limitation prevents the full presentation of these case studies, as they might deserve.

Tri-state Homes

In the 1980s a rash of moisture problems arose in homes in Minnesota, Wisconsin and Michigan by one innovative panelization manufacturer. The actual causes of the problem appeared to be rainwater entry at the foundation, together with few air paths for escaping moisture-laden air. The damage occurred along the paths of air egress. However, standard practice was viewed in court documents as being regulated in terms of relative permeances of interior and exterior papers. In order to assign fault, it was necessary for the courts to look to design decisions that deviated from condensation paradigm-based practice recommendations, rather than to actual causes. Since Tri-State, manufactured housing has felt obliged to include a vapor barrier on the warm side, though the industry is unable to identify which is the warm side for the ultimate product destination.

EIFS

A rash of cases involving rotting of sheathing beneath Exterior Insulation Finish Systems (EIFS), particularly in Wilmington NC and Vancouver BC led to severe penalties to designers and building professionals in those areas. EIFS systems had been used successfully for decades in Europe, on masonry systems without vapor barriers. In North America the problem was related to rainwater leakage at window, balcony and other details, together with the problem that sheathing is a substrate more susceptible to

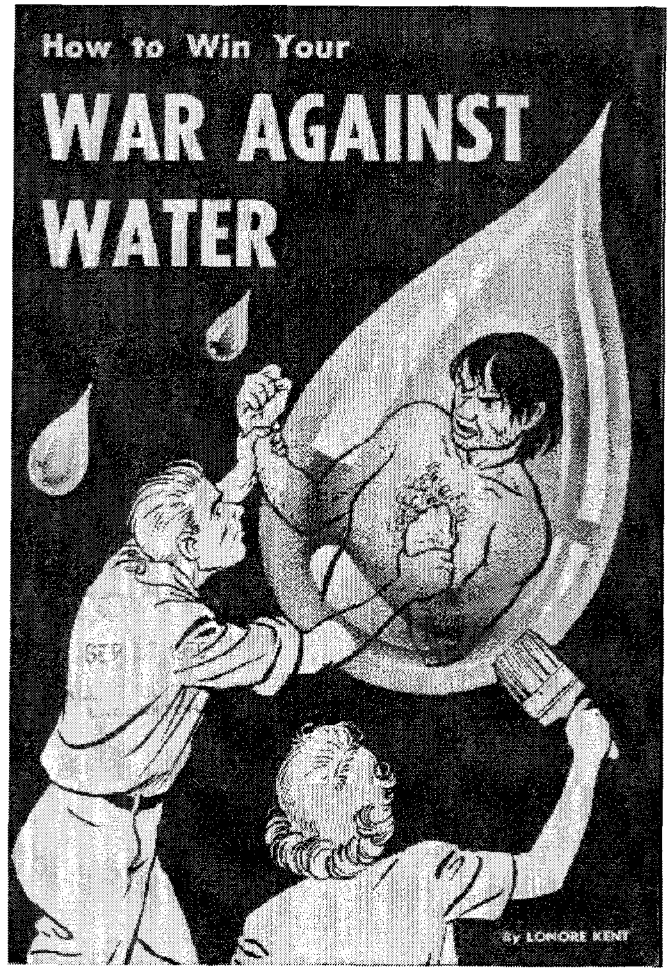

Fig. 2. Pamphlet cover from 1951. This was part of the campaign to sell the condensation paradigm, produced by the National Paint and Varnish Association.

mold growth than is masonry or concrete. Upon inspection it was found that the Vancouver buildings had, for the most part, polyethylene interior vapor barriers. A study by the National Research Council of Canada showed that the rotting would not have occurred, or would have been minimal, had the blanket prescription for interior poly not been followed. In Vancouver, in response to the crisis, the post of a Certified Building Envelope Specialist was created to review the work of architects related to rainwater management. EIFS survives, but the condensation paradigm that needlessly dictates the use of vapor barriers limits its widespread use.

SIPS panels in roof assemblies

Several manufacturers provide compact foam-core panels for use in steep roof assemblies. These panels may be prone to water problems at the joints, otherwise they appear to deliver excellent moisture performance. However the condensation paradigm dictates the use of attic ventilation in steep roof applications, so some manufacturers have compromised the structural and thermal performance in order to accommodate this requirement. Not only are air slots unnecessary and too small to overcome resistance to buoyant flow, they may also lead to deplorable fire performance, given the flammability of the unprotected core materials.

Historic Buildings

If the vapor barrier and attic ventilation arose as regulated practices in the period 1938-1948, then what performance might be expected from buildings from prior times? Frank Lloyd Wright's Wingspread (Racine WI) is classic[15]. The roof assembly, from outdoors in, contains flat roofing tiles, asphalted felt paper (later built-up roof, then modified bitumen), tongue-and-groove 1x 6 sheathing, densely compressed fiberglass insulation, spray-applied cellulose insulation, a spray-applied bitumen layer, air space, lath-and-plaster, and an interior wax coating (provided by the client, Herbert Johnson of Johnson Wax). There is no ventilation. Odd as it may seem to use a Frank Lloyd Wright roof assembly as a positive role model, work done from 1995-1997 on the roof assembly disclosed excellent vapor performance. The point here is not to recommend just one non-complying assembly for its climate and use, but to suggest that the wealth of historic assemblies for a climate can be used as models and starting points for design. The physical evidence of historic performance should supercede disallowances based on limited theory and prescription.

Progressive Architecture magazine, in its final days, asked where boldness in American design could be found, compared to that found in Europe and elsewhere. The notion that all walls must contain vapor barriers and all roof assemblies must contain ventilation undoubtedly stifles creativity. Building envelope assemblies that have layers of protection against rain, but are otherwise simple and compact usually demonstrate fine performance. Their use is often questioned by code officials and others for reasons grounded in either understanding or misunderstanding of the condensation paradigm.

2. Actual crises

Recently a flurry of concern for "toxic mold" has arisen in the courts and the press. It was provoked by a paper that linked the mold *Stachybotrys chartarum* to infant bleeding lung disease. This finding was challenged in 1999[16], nevertheless, the legal and media concerns for mold remain quite pronounced. Discussions of mold usually begin with the elements necessary for their growth, and moisture is the only item on the list subject to industry professionals' control. Unfortunately, when health or legal professionals turn to the literature they often find moisture-control code requirements that are predicated on the condensation paradigm. So blame is usually assigned in ways that fail to mirror actual causes and cures for mold problems.

Perhaps the greatest detriment in the condensation paradigm is not harm done by following its tenets, but in failing to study the improvements that are possible outside of the paradigm.

3. Dynamics of the delivery system

The sociology of the construction industry is well known to those who practice within it, even if it has not been subject to the study it deserves. Gutman's work is a shining exception.[17] An important defect arising from the condensation paradigm is the notion that there are, somewhere, experts who can intervene in an architect's design and render the design free of moisture problems. And there is a corollary imaginary figure in construction who, during the course of construction, can ensure effective water and vapor management for ultimate building performance. Such individuals are not found. For better or worse, water and vapor management occurs through the actions of designers in the everyday design process, and through the actions of builders in the process of normal construction. There is very little training for designers or builders in water management outside the condensation paradigm.

The failure of the condensation paradigm has led to a disquieting spread between the competing obligations of compliance and building performance. Conflicts are common between design and construction. Most disputes can be resolved contractually and amicably. "Condensation" problems on the other hand usually go unresolved because an effective framework for their resolution is missing. Already strained relations between designers and builders are further soured when "condensation" problems arise.

Current work

Efforts are underway a by members of ASTM (American Society for Testing and Materials) and ASHRAE (American Society of Heating Refrigerating and Air Conditioning Engineers) to develop standards and guidelines for conducting hygrothermal analyses of building envelope assemblies. The ASTM efforts are found in E241-00e1 Standard Guide for Limiting Water-Induced Damage to Buildings; the ASHRAE efforts are in progress through SPC-160P Design Criteria for Moisture Control in Buildings. Eventually, the ASHRAE Standard would serve as the basis for hygrothermal performance of building envelope design and construction. It could be referenced by code, used in offices, and support teaching modules in its use. ASHRAE 160P (which is not yet published) differs from the condensation paradigm in at least three major respects:

1. Moisture loads to the building envelope include rainwater entry past the weather protection and solar-driven vapor loads
2. Transient rather than steady-state modeling is used, which accounts for moisture storage in materials, and
3. Prevention of mold growth on organic surfaces is the principal criterion, using the International Energy Agency determination of monthly-average surface water activity of 0.8 as a mold-avoidance threshold.

What improvements in design and construction are possible under a better paradigm? Most of the moisture damage to building envelope assemblies (mold growth, corrosion, efflorescence) occurs on surfaces. Envelope assemblies without interior cavities, and the resulting surfaces, naturally resist such problems, though voids are often helpful as capillary breaks at the exterior. Compact (cavity-free) assemblies such as foam, masonry and concrete generally need no additional vapor protection. Most hybrid assemblies that include foam and other compact materials also show excellent performance and are adaptable to various climates. In fact, given the rarity of diffusion-flow moisture damage in buildings, vapor protection should probably not be widely applied as an early criterion in predicting future performance. In short, building envelopes that are well detailed for rain water management, and which take advantage of drying potential offered by sun and airflow, may perform well despite short-sighted predictions to the contrary.

Conclusion

The condensation paradigm states that building envelope assemblies can be judged for suitability and acceptability using a steady state analysis that, in its simplest interpretation, predicts the formation (or not) of condensation. This paradigm arose in the late 1930s to enhance the commercial interests of the insulation and paint industries, following the finding that painted wood-frame buildings exhibited greater paint peeling when insulated. The paradigm has been, since its inception, a very poor predictor of moisture conditions in buildings. Nevertheless, it is central to building codes and other guidance documents related to moisture control.

The condensation paradigm is not a satisfactory basis for hygrothermal design of building envelopes. It ignores much of significance in performance, most notably moisture storage in common materials such as wood and brick, the drying and vapor-drive effects of sunlight, and the role of water and air management in ensuring safe structures. Examples of conflict between performance and compliance are widespread, as seen in historic buildings before the introduction of the condensation paradigm, as well as in examples from afterward. Improved tools for estimating hygrothermal performance are available and also under development.

Damage that can be attributed to vapor drive under ambient (not solar-driven) pressures is quite rare. Vapor protection measures, at least the traditional measures of vapor barriers and attic ventilation, ought not to have the primacy of place accorded them by building codes. The palette of imagined building envelope assemblies should expand beyond those that comply with an outdated condensation paradigm.

Notes

1 Browne, F.L.1933. Some causes of blistering and peeling of paint on house siding. US Forest Products Laboratory No. R6, Madison Wi.

2 Jordan, C.A., Peck, E.C., Strange, F. A. and Teesdale, L.V., "Attic Condensation in Tightly Built Houses", Housing and Home Finance Agency Technical Bulletin no. 6, September 1948 pp. 29-46. Also in Housing and Home Finance Agency Technical Bulletin no. 8, January 1949, pp. 67-84. The issue of condensation in building envelopes was continued after this article by L.V. Teesdale, and for that reason his name is used in the discussion.

3 Rogers, T.S. 1952. "Opening of the Conference" in *Proceedings: Condensation Control in Buildings as Related to Paints, Papers, and insulating Materials.* Building Research Advisory Board (BRAB) National Research Council/National Academy of Sciences. Washington DC. p. 3

4 Ibid. p. 3

5 Rowley, F.B. 1938. A theory covering the transfer of vapor through materials. *ASHRAE Transactions.* No. 1134.July 1939. American Society of Heating Refrigerating and Air conditioning Engineers. Atlanta GA.

6 Rowley,1938, p. 41

7 Rowley, F.B., A.B. Algren and C.E. Lund, 1939. Condensation of moisture and its relation to building construction and operation. *Heating, Piping and air conditioning.* January 1939.

8 Rogers, T.S. "Preventing Condensation in Insulated Structures" Architectural Record March 1938, pp. 109-119

9 Rogers 1938. p. 109.

10 In simplest terms, the argument is this: during cold weather, cladding materials are kept at colder temperatures in insulated structures than in uninsulated structures. Lower temperatures at the same absolute humidity lead to higher relative humidties local to the cladding, and higher relative humidities lead to higher moisture contents.

11 L. Kent, *How to Win Your War Against Water* (Washington, DC: National Paint, Varnish & Lacquer Association, no date, stylistically early 1950s). and L. Kent, *How to The Menace of Moisture* (Washington, DC: National Paint, Varnish & Lacquer Association, no date.)

12 Rogers, T.S. 1952. "Opening of the Conference" in *Proceedings: Condensation Control in Buildings as Related to Paints, Papers, and insulating Materials.* Building Research Advisory Board (BRAB) National Research Council/National Academy of Sciences. Washington DC.

13 International Energy Agency, 1991. Annex XIV, Volume 2 Condensation and Energy : Guidelines and Practice. Available through Building Physics Laboratory, Catholic University, Leuven Belgium.

14 Burch, D. MOIST. One-dimensional hygrothermal building envelope performance modeling tool. National Institute for Standards and Technology.

15 Discussed in Rose, W. 1997. Control of moisture in the modern building envelope: the history of the vapor barrier in the United States 1923-1952. APT Bulletin, Vol. XVIII. No. 4, October 1997.

16 Centers for Disease Control (CDC) 2000. Update: Pulmonary Hemorrhage/Hemosiderosis Among Infants — Cleveland, Ohio, 1993-1996. *http://www.cdc.gov/mmwr/preview/mmwrhtml/mm4909a3.htm*

17 Gutman, Robert, 1988. Architectural practice: a critical review. Princeton Architectural Press, New York.