Benchmark Performance Analysis
Of An ECM-Modulated Air-To-Air Heat Pump
With A Reciprocating Compressor

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PURPOSE OF ECM BENCHMARK ANALYSIS

- Determine Limits Of Existing Modulating Technology
  - High efficiency drives and heat exchangers
  - Reciprocating compressors

- Demonstrate Use of Modulating Design Tool
  - Extension of Mark III heat pump design model
    - 4 types of modulating drives for comp. and fans
    - extended flow-range air-side H.T. correlations
    - charge inventory prediction and balancing
    - extensive 1- and 2-D parametrics
HARDWARE ASSUMPTIONS

Modulating Drives and Heat Exchangers

- Same Hardware Constraints As Highest SEER Modulating Unit
  - ECM-driven compressor and fans
  - Same compressor turndown ratios
    - 1 to 0.28 in heating and cooling
    - no heating-mode overspeed operation
  - Reciprocating compressor
  - Same [total Hx area] / [ton of cooling capacity]
COMPONENT EFFICIENCY REPRESENTATIONS

Modulating Drives, Compressors, and Fans

♦ Modulating Drive Efficiencies -- Compressors and Fans
  • Functions of speed and torque ratios
♦ Modulating Compressor Efficiency
  • Functions of speed and operating conditions
    – map-based from discrete frequency data
    – induction-to-ECM drive conversion built-in
♦ Modulating Fans
  • Efficiencies assumed constant as speed changes
    – ODF efficiency varies with coil ΔP characteristic
    – IDF efficiency fixed at 45% under all ΔP conditions
REFRIGERATION COMPONENT PERFORMANCE

Heat Transfer and Refrigerant Flow Control

- **Heat Exchangers**
  - Hx geometry of first-generation modulating unit
    - validated fin-and-tube Hx configurations
    - air-side area/ton scaled to SOA
  - Added internal and external surface augmentation
    - louvered fins on air-side
    - 150% multipliers to ref-side H.T. and ΔP
- **Idealized Variable-Opening Flow Control**
  - Fixed low values of evaporator superheat
    - 10 F° in cooling, 1 F° in heating
  - Condenser subcooling used as design variable
STEADY-STATE DESIGN APPROACH

Maximize COP At Four Conditions

♦ Cooling Mode
  • 95°F — Max speed, nominal design capacity, acceptable S/T ratio
  • 82°F — Min speed, min capacity, acceptable S/T ratio

♦ Heating Mode
  • 47°F — Min speed, min capacity, acceptable min supply temp
  • 17°F — Min speed, max capacity
Four-Point Strategy

- Nominal Design (at 95°F) Determines
  - Compressor size and maximum airflows
  - Required motor sizes
  - Hx area ratio and configuration
- Off-Design Analyses (at 82°F, 47°F, 17°F)
  - Determine air and refrigerant flow-control variables
    - fan speeds
    - condenser subcooling
  - At min or max compressor speeds
Nominal Design Analysis

- Optimization Variables
  - Interdependent
    - Compressor displacement
    - Nominal airflow rates -- indoor and outdoor
    - Indoor fraction of total area
    - Condenser subcooling
  - Weakly-interacting
    - # of coil rows and circuits -- indoor and outdoor
Nominal Design Analysis (continued)

- Assumptions
  - Design capacity of 2 1/2 tons cooling
  - Auto-sizing of motors to nominal conditions
    - compressor motor sized to 130% of rated Hp
    - fan motors sized to 75% of rated Hp
  - External ΔP of 0.15 inches water
  - 10 F° evaporator superheat
COOLING EER AND CAPACITY AT 95 F AMBIENT

\[ x = \text{capacity-constrained optimum} \]
COOLING EER AND CAPACITY AT 95 F AMBIENT

$Q_c = 30$ KBTuh

$Q_c = 28$ KBTuh

$EER_c = 12.0$

$EER_c = 11.5$

$EER_c = 11.0$

$x = \text{capacity-constrained optimum}$

NOMINAL INDOOR AIR FLOW (cfm)

INDOOR COIL AREA FRACTION
Off-Design Analysis

- Variables Optimized
  - Indoor and outdoor fan operating speed ratios
  - Condenser subcooling
- Design Constraints
  - Capacity -- Minimum or Maximum
  - Comfort Conditions -- S/T Ratios and Supply Temps
    - comparable to SOA reference unit
    - relaxed S/T ratio
COOLING EER AT 82 F AMBIENT

x = constrained-optimum for S/T of 0.83
o = constrained-optimum for S/T of 0.71
SENSIBLE-TO-TOTAL CAPACITY RATIO AT 82 F AMBIENT

$\times$ = constrained-optimum for S/T of 0.83
$\circ$ = constrained-optimum for S/T of 0.71
HEATING COP AT 47 F AMBIENT

x = supply-temperature-constrained optimum
SUPPLY AIR TEMPERATURE AT 47 F AMBIENT

\[ x = \text{supply-temperature-constrained optimum} \]
Fan Modulation Ranges Are Narrower Than The Compressor

OPTIMAL CONTROL STRATEGIES

MODULATION RATIO

AMBIENT TEMPERATURE (°F)

RELAXED S/T
LOW S/T

ODF
IDF
COMP
Drive and Overall Component Efficiencies Vary Considerably Over Operating Ranges

OPTIMAL OPERATING EFFICIENCIES

EFFICIENCY (%) vs AMBIENT TEMPERATURE (°F)
COMPARISON OF STEADY-STATE RESULTS

Cooling EER

- ECM Benchmark, Relaxed S/T
- ECM Benchmark, Low S/T
- SOA Reference
- SOA Alternative
- Modified First Generation
- First Generation

Ambient Temperature (°F)
COMPARISON OF STEADY-STATE RESULTS

Heating COP

- ECM Benchmark
- SOA Reference
- SOA Alternative
- Modified First Generation
- First Generation

Ambient Temperature (°F)
HEATING COP

x = high-speed design point
ο = low-speed design point
REQUIRED REFRIGERANT CHARGE — HEATING MODE

\[ x = \text{high-speed design point} \]
\[ o = \text{low-speed design point} \]
SEASONAL PERFORMANCE RESULTS

House-Loads-Based Seasonal Model

- Binned Weather For DOE Region IV City
  - Columbus, Ohio
- 1800 ft² House
  - HUD minimum insulation
- Nominal Unit Sizing Per DOE Procedure
  - Scaled unit capacity as needed
- Full Speed vs Ambient SS Performance Mapping
- Default $C_D$'s of 0.25
SEASONAL PERFORMANCE RESULTS

DOE Ratings Analysis

✦ Normalized Region IV Weather Profile
✦ Minimum DHR
✦ DOE Unit Performance Specification
  • Min, max, and intermediate speeds
  • At selected ambients
✦ Default $C_D$'s of 0.25
Predicted Seasonal Performance Factors
For SOA Reference and ECM Benchmark

(DOE Region IV--Nominal Unit Sizing)

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HSPF Gain for ECM Benchmark
Is Overpredicted By DOE Rating Procedure
(DOE Region IV – Nominal Unit Sizing)
50% Oversizing Gives A Large Boost
To Region IV Heating and Annual Performance
For High-Efficiency Modulating Units

(House-Loads-Based)
CONCLUSIONS

♦ For a Best-Case Optimized Design
  • Upper limit SEER of 20 with relaxed S/T ratios
  • Steady-state heating gains greater than cooling
  • Only 8% HSPF gains vs 29% SEER increase
    – for standard unit sizing
♦ Oversizing More Beneficial For Modulating Heat Pumps
♦ Lower-Cost Alternatives To Oversizing Need Evaluation
  • More compressor overspeed in heating mode
  • Use of a scroll compressor
♦ DOE Ratings Overestimate Typical HSPFs
CONCLUSIONS (continued)

- An Optimized Modulating Design Can Be Obtained
  - With 4-point approach
- Decisions Remain With Design Engineer
  - Rather than with black-box routines
- Modulating Design Model Is A Viable Desktop Tool
  - For optimizing air-to-air heat pumps
    - using built-in parametrics
    - and available contour plotting software
- Program Is Available To HVAC Industry
  - Can be used to optimize designs
    for pure refrigerant alternatives
    - e.g., Spatz -- 1991 CFC Alternatives Conference
UNRESOLVED ISSUES

Estimated Contributors To Predicted COP Gains

✦ First Level
  • Relaxed S/T ratios at lower speeds (cooling only)
  • Optimal air flow control
  • Internal and external H.T. augmentation

✦ Second Level
  • Closer motor sizing
    – fans -- especially indoor
  • Optimal refrigerant flow control

✦ Third Level
  • No line or reversing valve losses
  • No filters/chokes on ECM drives
  • Ideal circuiting and flow arrangement assumptions