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Simplified Computerized Design of Pneumatic Conveyors

Nandor Latincsics, USA

Summary

The purpose of the design guide outlined below is to obtain the system parameters, such as *relative pressure drops, velocities,* and blower data such as *flow and pressure values* for pressurized pneumatic conveying systems, with a single value of (constant) pipe diameter. The designs are based on the mean particle size of the conveyed material.

This method of design for pneumatic conveyor systems deals with pressurized systems only and gives results quickly for conveyors working either in the dilute or dense phase.

On the whole, the design calculations are based on well known methods and theories; it is the setting up of applicable equations, and the programming that provides quick, comprehensive results.

Nomenclature

Terms are listed in the order of occurrence in the programmed calculations

Input data

DPMEAN — Mean particle size, inch

RHOT — True density of conveyed material, lb/ft^3

DR — Delivery rate, lb/h

VS — Mass saltation velocity of material, ft/sec

DT — Inside diameter of conveying pipeline, inch

LAH — Length of air pipeline from intake to blower, horizontal, ft.

LAV — Length of air pipeline from intake to blower, vertical, ft.

LAHA — Length of air pipeline from blower to the point of introduction of material, horizontal, ft.

LAVA — Length of air pipeline from blower to the point of introduction of material, vertical, ft.

LCH — Length of conveying pipeline, horizontal, ft.

LCV — Length of conveying pipeline, vertical, ft.

CD — Drag Coefficient

RHOI — Density of gas at intake of blower, lb/ft^3

RHOGA — Density of gas at discharge of blower, lb/ft^3

TMAX — Max. permissible temperature of compressed gas, °R

TI — Intake temperature of conveying gas, °R

E — Voidage factor in vertical conveying lines

CP — Specific heat of conveying gas at constant pressure, $\frac{BTU}{lb - {}^\circ R}$

CV — Specific heat of conveying gas at constant volume, $\frac{BTU}{lb - {}^\circ R}$

ETAP — Polytropic efficiency of blower

ETAM — Mechanical efficiency of blower drive

$K = \frac{CV}{CP}$ — Ratio of specific heats of conveying gas

PI — Pressure of conveying gas at intake, psia

PA — Assumed system pressure drop, psi

PP — Estimated pressure drop through peripheral equipment such as intake filters, etc., psi

C1 — Constant, 144 in^2/ft^2

V1 through *V8* — Range of conveying gas velocities, assumed to suit the application, ft/sec

$KO = \frac{VDH}{VS}$ — Design factor, ratio of design superficial velocity to mass saltation velocity in horizontal conveying lines

N. Latincsics, M.S.M.E., P.E., Principal Engineer, Materials Handling Group, The Lummus Company, A Subsidiary of Combustion Engineering, Inc., 1515 Broad Street, Bloomfield, NJ 07003, USA

$KV = \frac{VDV}{VCH}$ — Design factor, ratio of design supfperficial velocity to choking velocity in vertical lines

*PAH*1 through *PAH*8, and *PAV*1 through *PAV*8 — Relative pressure drops at the respective gas velocities *V*1 through *V*8, in the horizontal and vertical intake lines, respectively psi/ft

System Parameters

R — Pressure ratio, see Eq. 1

N — Ratio of specific heats, see Eq. 2

*R*1 — Ratio of gas densities, see Eq. 4

A — Area of conveying lines cross-section, ft²

W — Relative mass flow rate in conveying pipeline,

$$\frac{lb}{ft^2 \times sec}$$

VDH — Design superficial gas velocity in horizontal conveying lines, ft/sec

VSV — Superficial material velocity in vertical conveying lines, ft/sec

VT — Terminal velocity of "falling" conveyed particle in vertical conveying lines, ft/sec

VCH — Choking velocity in vertical conveying lines, ft/sec

VDV — Design superficial velocity in vertical conveying lines,ft/sec

VD — Overall design superficial conveying gas velocity, ft/sec

VA — Average superficial conveying velocity based on compressive flow, ft/sec

$PAHA_n$ and *PAHD* — Design values of relative pressure drops through *LAH*, and at *VA* and V_n, respectively, psi/ft

PAHAD — Design value of relative pressure drop through *LAHA*, and at *VA*, psi/ft

PAVAD — Design value of relative pressure drop through *LAVA*, psi/ft

*PCH*1 through *PCH*8 — Profile of relative pressure drops in the horizontal conveying line *LHC*, at the respective velocities *V*1 through *V*8, psi/ft

PCHD — Relative pressure drop through *LHC* at *VD*, psi/ft

*PCV*1 through *PVC*8 — Profile of relative pressure drops through *LCV* at the respective values of *V*1 through *V*8, psi/ft

PCVD — Relative pressure drop through *LCV* at *VD*, psi/ft

Summary of Results

QA — Atmospheric gas flow at blower's discharge, ft³/min

Total PD — Total pressure drop through the system, calculated, psi

*R*2 — Pressure ratio, calculated, based on *Total PD*

QI — Intake flow of blower, based on polytropic process, ft³/min

*T*2 — Temp. of gas at blower's discharge, °R

VDMAX — Max. superficial velocity based on compressive flow, ft/sec

S/A — Solid to air ratio, lb/lb

HPA — Adiabatic horsepower of blower

HPGAS — Polytropic (gas) horsepower of blower, based on *ETAP*

HPRUN — Running horsepower of blower based on *ETAM*

*H*2 — Heat to be removed by aftercooler, not to exceed *TMAX*, BTU/h

QM — Mass flow rate through aftercooler, lb/h

*R*3 — Reduction factor, see Eq. 28a

VDR — Overall design superficial velocity, reduced due to removal of *H*2, ft/sec

VAR — Average superficial gas velocity reduced due to removal of *H*2, ft/sec

VDMAX — Max. superficial gas velocity, reduced, ft/sec

1. Introduction

The design process needs the input data listed in the nomenclature. Of these input data, the following are assumed initially for trial and error method of calculation:

DT — inside diameter of the conveying line
PA — system pressure

V_1 through V_8 — possible range of conveying gas velocities
V_s — mass saltation velocity

All other data, such as design factors *KO, KH, PAH,* etc. are obtained from process conditions, piping layout and reference data as detailed below.

The methods of system parameters design are detailed below, with guides for selecting the value of input data required for the calculations. The most important calculated system parameters are the *design and average superficial gas velocities* and the *relative design pressure drops at the average superficial gas velocity.*

The calculated system parameters are used to establish the total system pressure drop, intake and discharge flow, horsepower of blowers, air-to-solids ratio and heat exchanger data when needed.

With a summarized set of calculated data, it is possible to go back to the original set of input data, make comparisons and repeat calculations with changed input in case of significant differences.

The use of the outlined method was programmed and the programmed calculations are illustrated through examples.

Programmable calculators with about 2,300—2,400 programmable steps are especially suitable for these calculations.

The uncertainties associated with these calculations are the values of saltation velocity and design factors assumed. Experience will guide in selecting good values.

Fig. 1 shows the general arrangement of a pneumatic conveyor system, indicating the length of pipes with different flow and pressure conditions. This sketch uses the designations listed in the nomenclature.

Note that the vertical pipe lengths *LAV*, *LAVA* and *LCV* include the equivalent lengths of elbows.

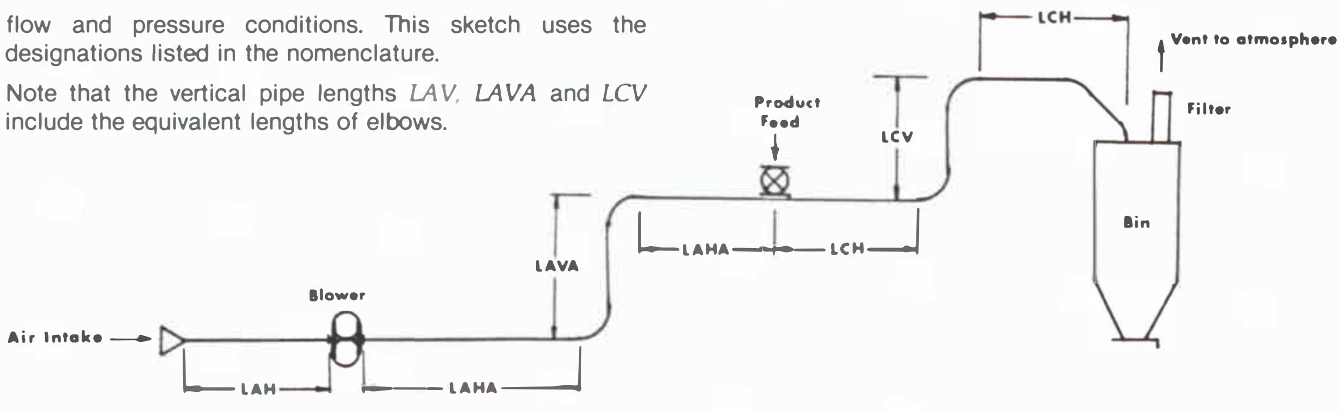

Fig. 1: Pneumatic conveyor — pressure system. General arrangement and designation of pipe lengths.

2. Calculation of System Parameters

With the assumption of the initial data, the system parameters can be calculated as follows:

1. The pressure ratio:

$$R = \frac{PI + PA}{PI} \quad (1)$$

2. The ratio of specific heats for polytropic compression:

$$N = \frac{1}{1 - \frac{K - 1}{K \times ETAP}} \quad (2)$$

3. The value of polytropic efficiency varies with different types of machines. Scheel [1] advises to use the following polytropic efficiencies:

   — Straight lobe rotary blowers: 0.66
   — Helical lobe rotary blowers: 0.78
   — Axial screw blowers: 0.74

   More detailed data may be obtained or evaluated from manufacturers' catalogs. Note that in cases when adiabatic conditions may be assumed, then $ETAP = 1$ and $N = K$.

4. The ratio of intake and discharge gas densities:

$$\frac{RHOA}{RHOI} = R^{1/N} \quad (3)$$

   If $R^{1/N} = R1$, then from Eq. 3, the atmospheric gas density at the discharge of the blower is

$$RHOA = R1 \times RHOI \quad (4)$$

5. The area of cross-section of the conveying line is:

$$A = \frac{DT^2 \pi}{4 \times 144} \quad (5)$$

6. The solid mass flow rate in the conveying line is:

$$W = \frac{DR}{3{,}600\, A} \quad (6)$$

7. Conveying Velocities:

   The design superficial velocity for dilute phase conveying is based on the following considerations:

   a) For cases of dilute phase conveying, in the horizontal conveying lines the superficial velocity has to be greater than the mass saltation velocity (or pick up velocity) for the material to be conveyed. For the horizontal lines, design factor *KH* is applied and the design velocity in the horizontal conveying lines is calculated:

$$VDH = KH \times VS \quad (7)$$

   The value of mass saltation or pick up velocities may be calculated, several methods are available and Zenz [2, 3,] and others Wen [4], Leung [5], offer different methods of such calculations. A wealth of experimental data is also available in the related publications. Using the applicable values of *VS* and the value *KH*, the design value of *VDH* can be calculated. For dilute phase conveying, since saltation should not occur:

   $KH > 1$, usually $KH = 1.1$—1.5

   Selection of the value will depend on choice between conservative design vs. smaller blower capacity.

   b) Saltation is permissible with dense phase conveying and therefore the value of design factor *KH* may be less than unity:

   $KH < 1$, usually $KH = 0.1$—0.5

   Again, the selection will depend on the choice between conservative design vs. small blower capacity and experience will guide. The general rule is that the higher the value of the saltation velocity, the lower the value *KH* may be. Low values, such as $KH = 0.1$ may be chosen in case of distributed particle sizes and high loads resulting in high saltation velocities.

   c) In the vertical lines the superficial gas velocity has to be greater than the choking velocity. Again, there are several methods available to calculate the choking velocity. Experience seems to indicate that most often the choking velocity is lower than the saltation velocity. However, for checking purposes, the following approximation may be used:

$$VCH = VT + \frac{VSV}{1\text{-}E} \quad (8a)$$

Here the terminal (free fall) velocity VT is:

$$VT = \sqrt{\frac{4 \times RHOT \times DP \times g}{3 \times RHOA \times CD \times 12}} \quad (8b)$$

In this equation, the drag coefficient CD can be calculated, taken from charts but for most applications $CD = 0.24$

The voidage factor E in Eq. 8a is less than unity and the following values can be used:

— for dilute phase, conservative designs, $E = 0.94$—0.98

— for dense phase design $E = 0.91$—0.94

The superficial particle velocity in the vertical line is calculated based on the mass flow rate:

$$VSV = \frac{DR}{3600 \times A \times RHOT} \quad (8c)$$

With the value of choking velocity calculated, the design superficial gas velocity for the vertical line can be established:

$$VDV = KV \times VCH \quad (8d)$$

Here the design factor for the vertical line is normally $KV = 1.25$—1.75

d) The selected overall design superficial gas velocity VD will be the higher value resulting from Eq. 7 or Eq. 8 d.

e) Since the gas flow in the conveying line is a "compressive" flow, the gas velocity used for system pressure drop calculation is the average velocity of the system:

$$VA = \frac{VD}{2} \times (1 + R1) \quad (9)$$

3. Calculation of Relative Pressure Drops

1. The relative design pressure drop, at near standard condition, at the average velocity, in the horizontal line, by interpolation is:

$$PAHD = \frac{PAH_{n+1} - PAH_n}{V_{n+1} - V_n} \times (VA - V_n + PAH_n) \quad (10a)$$

Here $V_n < VA < V_{n+1}$ and V_{n+1} is less than the maximum value of the preselected velocity range.

In the vertical line:

$$PAV_n = PAH_n + \frac{RHOI}{144} \quad (10b)$$

$$PAVD = PAHD + \frac{RHOI}{144} \quad (10c)$$

2. The relative pressure drops in the lines carrying air only, at atmospheric condition, calculated with the average velocity are as follows:

$$PAHA_n = PAH_n \times R1 \quad \text{and} \quad (11a)$$
$$PAHAD = PAHD \times R1 \quad (11b)$$

$$PAVA_n = PAV_n \times R1 \quad \text{and} \quad (12a)$$
$$PAVAD = PAVD \times R1 \quad (12b)$$

3. The relative pressure drop in conveying lines:

There is wide range of theoretical and experimental methods available to determine the pressure drops. The formulas listed below are based on refs. [1] and [2].

a) *Dilute Phase Conveying:*

In the horizontal conveying lines:

$$PCH_n = PAHA_n \left(1 + \frac{W}{V_n + RHOGA}\right) \quad (13a)$$

and

$$PCHD = PAHAD \left(1 + \frac{W}{V_A \times RHOGA}\right) \quad (13b)$$

In the vertical conveying lines:

$$PCV_n = PAHA_n \times \left(1 + \frac{W}{V_n \times RHOA}\right) + \frac{RHOA}{144} + \frac{W}{144 \times (V_n - V_T)} \quad (14a)$$

and:

$$PCVD = PAHAD \times \left(1 + \frac{W}{VA \times RHOA}\right) + \frac{RHOA}{144} + \frac{W}{144 \times (VA - V_t)} \quad (14b)$$

b) *Dense Phase Conveying:*

In the horizontal lines, the pressure drop may be determined using the methods outlined in refs. [2], [3]. The following relationship seems to agree reasonsably well with experimental results:

$$PCH_n = 0.0255 \times \left(\frac{DPMEAN}{DT}\right)^{\cdot 25} \times \frac{W}{V^{0.55}} + PAHA_n \quad (15a)$$

$$PCHD = 0.0255 \times \left(\frac{DPMEAN}{DT}\right)^{\cdot 25} \times \frac{W}{VA^{0.55}} + PAHAD \quad (15b)$$

For the vertical lines, Eqs. 14a, b can be applied.

c) The programmed calculation will give the values of PCH_n, PCV_n, $PCHD$, $PCVD$. Thus, checking the values it can be established if the value of design superficial gas velocity was optimally established from the point of view of relative pressure drops.

4. Summary of Results — Blower, Heat Exchanger, Data

With the system parameters and relative pressure drops calculated, the summary of characteristics of the whole conveying system can be calculated.

1. Design velocity, based on VDH or VDV, which ever is higher.

2. The total pressure drop of the system:

$$Total\ PD = LAH \times PAHD + LAV \times PAVD + LAHA \times PAHAD + LAVA \times PAVAD + LCH \times PCHD + LVC \times PCVD + PP + \frac{W \times VD}{4640} \quad (16)$$

Note that the first two terms represent the pressure drops in the intake air line. The calculation is based on the terms of *PAHD*, *PAVD* and on the assumption that the line size and velocity are the same as with the discharge lines of the blower. This is a gross simplification but errs on the safety side. Note furthermore that the last term represents the pressure drop due to acceleration of the material fed into the conveying line.

3. The actual pressure ratio:

$$R2 = \frac{PI + Total\ PD}{PI} \quad (17)$$

4. The atmospheric flow at the blower's discharge:

$$QA = A \times VD \times 60 \quad (18)$$

5. The intake flow, based on polytropic compression:

$$QI = QA \times (R2)^{1/N} \quad (19)$$

6. The temperature of discharge gas, based on polytropic compressor:

$$T2 = T1 \times (R2)^{\frac{N-1}{N}} \quad (20)$$

7. The maximum velocity at the end of the system:

$$VDMAX = \frac{QI}{60 \times A} \quad (21)$$

8. The solid to air ratio of the system:

$$\frac{S}{A} = \frac{DR}{60 \times RHOI \times QI} \quad (22)$$

9. The adiabatic horsepower of the blower:

$$HPA = \frac{144}{33000} \times \frac{K}{K\text{-}1} \times PI \times QI \times (R2^{K-1/K}\text{-}1) \quad (23)$$

10. The polytropic gas horsepower of the blower:

$$HPGAS = \frac{HPA}{ETAP} \quad (24)$$

11. The running horsepower of the blower:

$$HPRUN = HPGAS/ETAM$$

12. After cooler is required if the discharge temperature of the blower is higher than the maximum permissible gas temperature, i.e.,

$$T2 > TMAX \quad (25)$$

13. The heat to be removed by the after cooler:

$$H2 = 60 \times QI \times RHOI \times CV \times (T2\text{-}TMAX) \quad (26)$$

14. The mass flow rate through the aftercooler:

$$QM = 60 \times QI \times RHOI \quad (27)$$

15. With negligible pressure drop across the aftercooler assumed, the flow rates and velocities will reduce in proportion to the temperature ratio, i.e.:

$$R3 = \frac{TMAX}{T2} \quad (28a)$$

With this, the reduced velocities:

The reduced *design* velocity:

$$VDR = R3 \times VD \quad (28b)$$

The reduced *average* velocity:

$$VAR = R3 \times VA \quad (28c)$$

The reduced *max.* velocity:

$$VDMAXR = R3 \times VDMAX \quad (28d)$$

The reduced value of design velocity has to be checked against the saltation velocity. The calculation has to be repeated for dilute phase conveying when $VDR < VS$ and has to be repeated for both dense and dilute phase conveying when $VDR < VCH$.

5. Programmed Calculations

These consist of the following:

— The input data, including a selected spectrum of velocities, $V1$ through $V10$. Assumed values are *DT, PA, PP, KH, KV, VS. PAHA* values, pertaining to *VA* and *DT* values are obtained from gas flow vs. pressure drop tables.

— Calculations based on Eqs. 1 through 28

— Selection subroutine to calculate relative pressure drop values based on calculated value of *VD*

— Selection subroutine for *VD*.

— Error message, if $VD > V10$

— Calculation for full spectrum of PCH_n and PCV_n

— Print-out of inputs, parameters, pressures (drop), summary of system data, cooler data.

Since the calculations are based on assumed values, program should be rerun if $PA < Total\ PD$ or especially where $PA << Total\ PD$. In case of very high values of *Total PD*, larger values of *DT* should be assumed.

6. Examples

1st Example

Dry, powdered chemical solids are to be conveyed a distance of 670 ft at a rate of 10,000 lb/h, in dilute phase. Air temperature is limited to 580 °R. For other input data and results, see print-out of programmed calculations. This conveyor is running with 10 psig capacity blower for several years. System and program results are in reasonably close agreement (Fig. 2).

2nd Example

Pulverized material is to be conveyed a distance of 775 ft, at a rate of 41,360 lb/h, dense phase. For other input data and results, see print-out of programmed calculations. The high

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DILUTEPHASE

INPUTDATA

DPMEAN=   0.0058
RHOT=       94.0
DR=        10000
VS=           90
DT=         8.30
LAH=           8
LAV=           0
LAHA=         20
LAVA=          0
LCH=         672
LCV=          74
CD=        0.240
RHOI=     0.0740
TMAX=     580.00
T1=       528.00
E=         0.960
CV=        0.177
ETAP=      0.680
ETAM=      0.980
K=         1.400
PI=       14.500
PA=        5.000
PP=        0.200
C1=      144.000

V1=         20.0
V2=         30.0
V3=         41.6
V4=         50.0
V5=         83.0
V6=        116.0
V7=        150.0
V8=        200.0
KH=         1.10
KV=         1.25

PAH1=   0.000125
PAH2=   0.000275
PAH3=   0.000500
PAH4=   0.000700
PAH5=   0.002000
PAH6=   0.004000
PAH7=   0.006000
PAH8=   0.011500

RESULTS

PARAMETERS

R=        1.344828
N=        1.724638
R1=       1.187422
RHOA=     0.087869
A=        0.375737
W=        7.392885
VDH=     99.000000
VSV=      0.078648
VT=       9.575921
VCH=     11.542113
VDV=     14.427642
VD=      99.000000
VA=     108.277378

PRESSURES

PAHD=     0.003532
PAHAD=    0.004194
PAVD=     0.004046
PAVAD=    0.004804

PCH1=     0.000773
PCH2=     0.001242
PCH3=     0.001794
PCH4=     0.002230
PCH5=     0.004782
PCH6=     0.008195
PCH7=     0.011121
PCH8=     0.019400
PCHD=     0.007453

PCV1=     0.006308
PCV2=     0.004366
PCV3=     0.004008
PCV4=     0.004110
PCV5=     0.006092
PCV6=     0.009287
PCV7=     0.012096
PCV8=     0.020280
PCVD=     0.008583

SUMMARY

VD=           99.00
QA=         2231.88
TOTAL PD=      6.11
R2=            1.42
QI=         2736.96
T2=          612.12
VDMAX=       121.40
S/A=           0.82
HPA=          64.09
HPGAS=        94.25
HPRUN=        96.17

COOLER DATA
H2=        69086.27
QM=        12152.12

REDUCED VALUES

R3=            0.95
VDR=          93.81
VAR=         102.60
```

Fig. 2: Example 1: Dilute phase — computer calculations

```
DENSE PHASE

INPUT

DPMEAN=   0.0041
RHOT=       87.3
DR=        41360
VS=          200
DT=         5.00
LAH=          30
LAV=           0
LAHA=        100
LAVA=          0
LCH=         775
LCV=          50
CD=       0.2600
RHOI=     0.0750
TMAX=     635.00
T1=       526.00
E=         0.920
CV=        0.177
ETAP=      0.680
ETAM=      0.950
K=         1.400
PI=       14.700
PA=       30.000
PP=        0.200
C1=      144.000

V1=         20.0
V2=         30.0
V3=         40.0
V4=         50.0
V5=         60.0
V6=         70.0
V7=         80.0
V8=        100.0
KH=         0.18
KV=         1.40

PAH1=   0.000200
PAH2=   0.000440
PAH3=   0.000780
PAH4=   0.000950
PAH5=   0.001700
PAH6=   0.002300
PAH7=   0.003550
PAH8=   0.004800

RESULTS

PARAMETERS

R=        3.040816
N=        1.724638
R1=       1.905694
RHOA=     0.142927
A=        0.136354
W=       84.257900
VDH=     36.000000
VSV=      0.965153
VT=       5.870321
VCH=     17.934740
VDV=     25.108636
VD=      36.000000
VA=      52.302489

PRESSURES

PAHD=     0.001123
PAHAD=    0.002139
PAVD=     0.002115
PAVAD=    0.004031

PCH1=     0.070044
PCH2=     0.056576
PCH3=     0.049068
PCH4=     0.043896
PCH5=     0.041310
PCH6=     0.039359
PCH7=     0.039264
PCH8=     0.037893
PCHD=     0.043196

PCV1=     0.054019
PCV2=     0.042557
PCV3=     0.041530
PCV4=     0.037407
PCV5=     0.046873
PCV6=     0.051413
PCV7=     0.065504
PCV8=     0.070281
PCVD=     0.039849

SUMMARY

VD=           36.00
QA=          294.52
TOTALPD=      36.57
R2=            3.49
QI=          607.73
T2=          889.10
VDMAX=        74.28
S/A=          15.12
HPA=          58.52
HPGAS=        86.05
HPRUN=        90.58

COOLER DATA

H2=       122996.28
QM=         2734.78

REDUCED VALUES

R3=            0.71
VDR=          25.71
VAR=          37.35
VDMAXR=       53.05
```

Fig. 3: Example 2: Dense phase — computer calculations

delivery rate and density result in an estimated 200 ft/sec saltation velocity, a high value. Therefore, the application calls for dense phase conveying. VS = 200 ft/sec and KH = 0.18 are chosen as design basis. It should be noted that an aftercooler is needed and $VDR < VD$, $VDR > VDV$ (Fig. 3).

Further assessment of the results of both examples are left to the reader.

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