Drying medium – modelling and process evaluation

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Abstract

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Natural gas is used as a heat source in the majority of modern drying plants in agriculture. The input gas is a mixture of natural gas and atmospheric air. With burning, the composition of this mixture changes. Drying medium is a mixture of hot combustion gases from natural gas and atmospheric air added. The thermic parameters of natural gas and atmospheric air are permanently constant. The authors present their method of the calculation of thermodynamic parameters of the drying medium. They elaborated two computer programmes in Q-Basic for the calculation related to the drying medium with temperatures in the range 100–200°C.

Keywords: natural gas; drying medium; computer program

Drying is a necessary process in agriculture for the final treatment of forages and grains.

In modern drying appliances, mixtures of combustion gases from natural gas with added atmospheric air are used as the drying medium.

The process of drying is explained in detail in specific literature by the authors Maltry and Pötke (1966), Valchař et al. (1967), Imre (1974), Pabis (1965, 1982). In this, Pabis (1965, 1982) presented his special knowledge gained in USA from Henderson. In the paper by Imre (1974), a computer program is given for the drying process modelling.

In their work, the authors try, to reach the most precise calculations of the drying medium parameters by using the gas mixtures thermodynamics according to Havelka et al. (1989) and Vitázek (2006), and precise parameters of individual gases coming from the tables by Ražnjevič (1969). The authors constat the best oldish description of fuel gases combustion by Kasatkin (1957).

Natural gas is used as a heat source in the majority of modern drying plants in agriculture. The source of the drying medium is a gas burner with a mixing chamber. The input gas mixture consists of natural gas and atmospheric air. With burning, the composition of this mixture changes as given by Vitázek (2008).

The quality parameters of natural gas are periodically published by SPP Bratislava (2010), Slovak Gas Industry in Bratislava. The quality parameters of atmospheric air and natural gas are permanently constant. Therefore, the authors state that one comprehensive elaboration suffices in many cases of research and practice.

The authors present here their method of the thermodynamic parameters calculation for the drying medium concerned. For this calculations, a computer program in Q-Basic was elaborated.

MATERIAL AND METHODS

The authors present the basic quality parameters of natural gas from the year 2009, the basic quality parameters of atmospheric air, stoichiometric relations for the oxidation of natural gas. With this knowledge,

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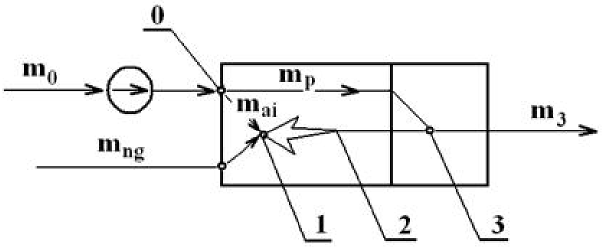

Fig. 1. Scheme of the mass flow in the burner chamber

they elaborated an analytical model of ideal burning of natural gas and of drying medium as a mixture of combustion gases with added atmospheric air.

For this analysis, they used the thermodynamics of ideal gases, thermodynamics of gas mixtures, and tables of quality parameters of individual gases as gived in the publication by Ražnjevič (1969).

They derived the relations for characteristic indexes of the drying medium analysed.

Model of drying medium

The scheme of the source of the drying medium, which is a gas burner with a mixing chamber, is shown in Fig. 1. The process of the drying medium creation is demonstrated in *i*–*x* diagram of wet air (wet gas) in Fig. 2. An air fan supplies atmospheric air m_0 in quality state, point 0. In the gas burner the first part of this air, stoichiometric part m_{0i}, is mixed with natural gas m_{ng}, state point 1. The quality of this mixture changes with burning into ideal combustion gases m_2, state point 2. These ideal combustion gases m_2 are mixed in the mixing chamber with the second part of the atmospheric air, added atmospheric air m_p, by which the final mixture is created, i.e. hot drying medium m_3, state point 3.

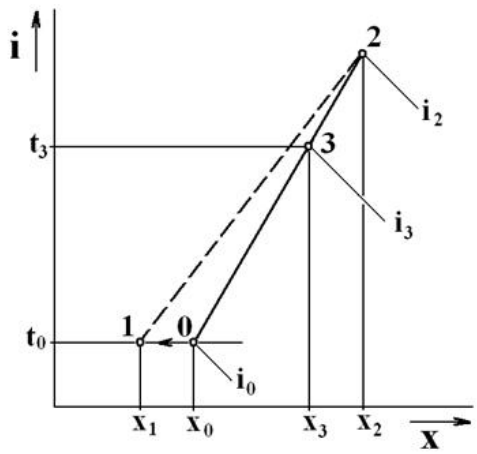

Fig. 2. Scheme of *i-x* diagram of wet air

Natural gas

SPP Bratislava published on the internet the average quality characteristics of natural gas in the year 2009.

Basic quality values:

Trade unit of natural gas:

1 m^3, t = 15°C, p = 101.325 kPa, φ = 0

Density	ρ_{ng}	= 0.7048 kg/m^3
Relative density	ρ_{ng}	= 0.5751
Heat value	Q_i	= 9.563 kWh/m^3 = 34.427 MJ/m^3 = 48.98 MJ/kg
Heat of combustion	Q_s	= 10.6077 kWh/m^3 = 38.188 MJ/m^3 = 54.32 MJ/kg

Average Molar concentrations (%):

Methan (CH_4)	x = 96.806
Etan (C_2H_6)	x = 1.4617
Propan (C_3H_8)	x = 0.6575
Carbon dioxyd (CO_2)	x = 0.2258
Nitrogen (N_2)	x = 0.8558

Average Mass concentrations:

Carbon	c	= 0.7378
Hydrogen	h	= 0.24279
Carbon dioxyd	co_2	= 0.006
Nitrogen	n_2	= 0.0145
Average value of Molar mass	M_{ng}	= 16.56 kg/mol
Average value of Gas constant	r_{ng}	= 502.04 J/kg K

Atmospheric air

Quality parameters from Chyský (1977). Atmospheric air serves as a source of oxygen for natural gas burning.

Average Mass concentrations:

Nitrogen	σ_{aN_2}	= 0.75524
Oxygen	σ_{aO_2}	= 0.23144
Carbon dioxyd	σ_{aCO_2}	= 0.01282
Argon et add.	σ_{aAr}	= 0.0005

RESULTS

Stechiometric relations

Ideal combustion of natural gas is described with basic chemical equations for the burning of 1 kg of natural gas.

$$C + O_2 = CO_2 \quad (1)$$

$$1\ \text{kg C} + 2.6642\ \text{kg}\ O_2 = 3.6642\ \text{kg}\ CO_2$$

$2\,H_2 + O_2 = 2\,H_2O$ (2)
$1\text{ kg } H_2 + 7.9381\text{ kg } O_2 = 8.9381\text{ kg } H_2O$

Mass of oxygen necessary for ideal combustion of 1 kg of natural gas:

$$m_{O_2i} = 2.6642 \times c + 7.9381 \times h = 3.9049\text{ kg } O_2 \quad (3)$$

The smallest mass of atmospheric air necessary for ideal combustion of 1 kg of natural gas:

$$m_{ai} = \frac{m_{O_2i}}{\sigma_{aO_2}} = \frac{3.9049}{0.23144} = 16.8722 \quad \text{kg} \quad (4)$$

New gases produced by natural gas burning:

Carbon dioxyd $m_{CO_2} = 3.6642 \times c = 2.700\text{ kg } CO_2$ (5)

Water steam $\Delta m_W = 8.94567 \times h = 2.1881\text{ kg } H_2O$ (6)

The residual mass of intacted gases from natural gas after combustion of 1 kg of natural gas:

Carbon dioxyd $m'_{CO_2} = 0.00433\text{ kg } CO_2$ (7)

Nitrogen $m'_{N_2} = 0.0142\text{ kg } N_2$ (8)

Analytic model of combustion

Ideal combustion of 1 kg of natural gas: the air fan supplies atmospheric air m_0 from which a stechiometric part m_{ai} is completed with 1 kg of natural gas and the mixture changes by burning into ideal hot combustion gases.

Atmospheric air – mass flow:
Dry part mass $m_{0d} = m_{ai}$ (9)

Moist part mass $m_{0W} = m_{ai} \times x_0$ (10)

Whole mass $m_{0C} = m_{ai} \times (1 + x_0)$ (11)

Inflammable mixture of atmospheric air and natural gas:
Natural gas mass $m_{ng} = 1$ kg

Dry part mass $m_{1d} = m_{0d} + m_{ng}$ (12)

Moist part mass $m_{1W} = m_{0W}$ (13)

Whole mass $m_{1C} = m_{1d} + m_{1W} = m_{ai} \times (1 + x_0) + 1$ (14)

Specific humidity $x_1 = m_{1W}/m_{1d}$ (15)

Ideal hot combustion gases:
Dry part mass $m_{2d} = m_{1d} - m_{O_2i} + m_{CO_2}$ (16)

Moist part mass $m_{2W} = m_{0W} + \Delta m_W$ (17)

Whole mass $m_{2C} = m_{2d} + m_{2W}$ (18)

Specific humidity $x_2 = m_{2W}/m_{2d}$ (19)

Enthalpy of the inflammable gas mixture:

$$I_2 = (m_{ai} \times c_{pa} + m_{ai} \times x_0 \times c_{pW} + m_{ng} \times c_{png}) \times t_0 \quad (20)$$

Enthalpy of ideal hot combustion gases:

$$I_3 = I_2 + m_{ng} \times Q_i \times \eta_b \quad \rightarrow \quad i_3 = I_3 / m_{2C} \quad (21, 22)$$

Drying medium

Drying medium is a mixture of hot ideal combustion gases from natural gas m_2 and added atmospheric air m_p which is the second part of the atmospheric air flow supplied with the air fan. The calculation is given for 1 kg of natural gas.

Atmospheric air – mass flow:
Inflammable gas mixture – dry part mass

$$m_{0d} = m_{ai} + m_{pd} \quad (23)$$

Added atmospheric air – coefficient of added air

$$\alpha = m_{0d} / m_{ai} \quad (24)$$

Added atmospheric air – dry part mass

$$m_{pd} = m_{ai} \times (\alpha - 1) \quad (25)$$

Added atmospheric air – moist part mass

$$m_{pW} = m_{ai} \times (\alpha - 1) \times x_0 \quad (26)$$

Added atmospheric air – whole mass

$$m_{pC} = m_{ai} \times (\alpha - 1) \times (1 + x_0) \quad (27)$$

Hot drying medium:
Dry part mass

$$m_{3d} = m_{2d} + m_{pd} = m_{ai} \times \alpha - m_{O_2i} + m_{CO_2} + m'_{CO_2} + m'_{N_2} \quad (28)$$

Moist part mass

$$m_{3W} = m_{2W} + m_{pW} = m_{ai} \times \alpha \times x_0 + \Delta m_W \quad (29)$$

Whole mass

$$m_{3C} = m_{3d} + m_{3W} \quad (30)$$

Specific humidity

$$x_3 = m_{3W} / m_{3d} \quad (31)$$

From this relations the authors derived the mass concentrations of individual gases in this hot drying medium

Nitrogen

$$\sigma_{3N_2} = (m_{ai} \times \alpha \times \sigma_{aN_2}) / m_{3C} \quad (32)$$

Oxygen

$$\sigma_{3O_2} = (m_{ai} \times (\alpha - 1) \times \sigma_{aO_2}) / m_{3C} \quad (33)$$

Carbon dioxyd

$$\sigma_{3CO_2} = (m_{ai} \times \alpha \times \sigma_{aCO_2} + m_{CO_2} + m'_{CO_2}) / m_{3C} \quad (34)$$

Argon et add.

$$\sigma_{3Ar} = (m_{ai} \times \alpha \times \sigma_{aAr}) / m_{3C} \quad (35)$$

Humidity

$$\sigma_{3W} = (m_{ai} \times \alpha \times x_0 + \Delta m_W) / m_{3C} \quad (36)$$

Drying medium – Molar mass

$$M_3 = 1/(\sum \sigma_i / M_i) \quad (37)$$

Drying medium – Gas constant

$$r_3 = 8{,}314.4 / M_3 \quad \text{(J/kg K)} \quad (38)$$

Heat balance of the drying medium: on combustion of 1 kg of fuel gas the reaction heat is released – heat value Q_i – and the enthalpy of combustion gases compared to the ambient neighbourhood increases by:

$$\Delta I_3 = m_{ng} \times Q_i \times \eta_b = 1 \times Q_i \times \eta_b \quad \text{(kJ)} \quad (39)$$

Ražnjevič (1969) tables for gas enthalpy are composed in such manner that the values $i_i = 0$ are assigned to the temperature $t = 0°C$. When using these tables, it is necessary to add a conversion amendment that represents the residual difference of enthalpy between the temperatures t_0 and 0°C:

$$\Delta I_{30} = \sum m_{3i} \times i_{3i} = \sum m_{3i} \times c_{pi} \times t_0 \quad \text{(kJ)} \quad (40)$$

The enthalpy of the combustion gases from 1 kg of fuel gas to 0°C is then:

$$I_3 = \Delta I_3 + \Delta I_{30} \quad \text{(kJ)} \quad (41)$$

and specific enthalpy:

$$i_3 = I_3 / m_{3C} \quad \text{(kJ/kg)} \quad (42)$$

By means of linear regression, the authors have obtained linear regression relations from Ražnjevič (1969) tables for all individual gases in the given fuel gas for temperatures 100–300°C with excellent regression coefficient r as follows:

$$i_i = b_i \times t - a_i \quad (43)$$

The enthalpy of the gas mixture (hot drying medium) is

$$i_3 = \sum i_{3i} \times \sigma_{3i} = \sum b_i \times \sigma_{3i} \times t_3 - \sum a_i \times \sigma_{3i} \quad (44)$$

From this relation, the relation is derived for the temperature of the hot drying medium

$$t_3 = (i_3 - \sum a_i \times \sigma_{3i}) / \sum b_i \times \sigma_{3i} \quad (45)$$

The enthalpy $i_{3(1+x)}$ for the work with i–x diagram of wet air is the sum of the enthalpy of 1 kg of dry gases and that of x_3 kg of moisture with its specific heat of evaporation

$$i_{3(1+x)} = i_{3dg} + x_3 \times (2{,}500 + i_{3W}) \quad \text{(kJ/kg}_{dg}\text{)} \quad (46)$$

That is to be calculated using the relation:

$$i_{3(1+x)} = i_3 \times (1 + x_3) + x_3 \times 2{,}500 \quad \text{(kJ/kg}_{dg}\text{)} \quad (47)$$

Characteristic indexes

In this chapter, the measured natural gas consumption $\dot{V}_{ng}$ m^3/h is the basis for the calculations of the characteristic indexes.

Natural gas – Mass flow

$$\dot{m}_{ng} = \dot{V}_{ng} \times \rho_{ng} \quad \text{(kg/s)} \quad (48)$$

Atmospheric air (input volume flow)

$$\dot{V}_0 = (m_{ai} \times \alpha \times (1 + x_0) \times \dot{m}_{ng}) / \rho_0 \quad \text{(m}^3\text{/s)} \quad (49)$$

Gas burner performance

$$P = \dot{m}_{ng} \times Q_i \times \eta_b \quad \text{(W, kW, MW)} \quad (50)$$

Hot drying medium (output volume flow)

$$\dot{V}_3 = (m_{3C} \times \dot{m}_{ng} \times r_3 \times T_3) / p_a \quad \text{(m}^3\text{/s)} \quad (51)$$

Hot drying medium (volumetric concentrations of oxygen and carbon dioxide)

$$x_{3O_2} = \sigma_{3O_2} \times M_3 / M_{O_2}$$

$$x_{3CO_2} = \sigma_{3CO_2} \times M_3 / M_{CO_2} \quad (52, 53)$$

Hot drying medium (mass concentrations of individual gases)

$$\dot{m}_{3i} = m_{3C} \times \dot{m}_{ng} \times \sigma_{3i} \quad \text{(kg/s)} \quad (54)$$

Drying medium example

The authors present the drying medium parameters, calculated for the drying of cereals at about 120°C.

Given values:

Given coefficient of added air α = 26

Average consumption of natural gas 10 m^3/h

Atmospheric air: t = 15°C, p = 100 kPa, φ = 60%

Efficiency of gas burner η_b = 98%

Calculated values:

Performance of the gas burner P = 93.9 kW

Atmospheric air, input volume flow 0.717 m^3/s

Drying medium, temperature t_3 = 121.2°C

Drying medium mass flow 0.866 kg/s

Drying medium volume flow 0.982 m^3/s

Drying medium enthalpy $i_{3(1+x)}$ = 153.3 kJ/kg_{dg}

Program in Q-Basic

The authors elaborated two computer programs in Q-Basic for the modelling of a specific drying medium and evaluation of the measured process values in a drying appliance, for drying medium with temperatures 100–200°C. They enable a quick and precise calculation of the parameters for the given drying medium.

These programs consists of three parts:

1. Introduction part. The user introduces the basic parameters of the process. This is a very simple activity not requiring the knowledge of the theory and of the thermodynamic parameters of the gases;
2. Program for the realisation of calculations, in which all necessary parameter values are introduced coming from thermodynamic tables;
3. Calculation report. This is a particular report with all initial information and input values, and with the calculated characteristic values and indexes.

DISCUSSION

The authors divided the whole process of drying into two parts:

1. hot drying medium creation,
2. reduction of the moisture content in the dried material by means of evaporation.

In this work, the authors present a method for precise mathematical modelling of hot drying medium with temperature 100–300°C for drying agricultural products in food quality.

SPP in Bratislava presents perfect information on internet on the composition and thermodynamic parameters of the natural gas delivered. The authors used it in this work. The drying medium is a mixture of five individual gases: N_2, O_2, CO_2, H_2O, Ar + inert. gases. The authors used the enthalpy tables presented in the publication by Ražnjević (1969). In this work, they used the relations from linear regression for temperatures 100–300°C, where all the regression coefficients were better than 0.999. The authors have used and presented special literature from recent time, which means all the time really significant.

The authors prepare a complex monograph "Theory of drying" in which they will present all their work done in this scientific branch.

CONCLUSION

The presented method enables precise calculations of the thermodynamic parameters of the hot drying medium consisting of a mixture of combustion gases from natural gas and added atmospheric air, in which the changes of the parameters with temperature are respected.

This calculation is very laborious. Therefore, practical use of this advantageous method is connected with a computer programme.

The presented method of the calculation of the thermodynamic parameters of the drying medium with natural gas is to be used with a great advantage in practice for the evaluation of the control measurements in drying plants and also for precise modelling of the drying medium parameters in the research into the drying processes. Using the computer program, this calculations are quick and precise.

References

Havelka J., Látal S., Navrátil S., 1989. Teplotechnika a hydrotechnika (Thermotechnics and Hydromechanics). Bratislava/Prague, Príroda/SZN: 352.

Chyský J., 1977. Vlhký vzduch (Wet Air). Prague, SNTL: 160.

Kasatkin A.G., 1957. Základní pochody a zařízení chemické technologie (Basic Processes and Appliances of Chemical Technology). Prague, SNTL: 415.

Imre L., 1974. Szárítási közikönyv (Manual of Drying). Budapest, Müszaki Könyvkiado: 1122.

Maltry W., Pötke E., 1966. Technika poľnohospodárského sušiarenstve (Technics of Drying in Agriculture). Bratislava, SVPL: 340.
Pabis S., 1965. Suszenie plodów rolnych (Drying of Agricultural Products). Warszawa, PWRiL: 312.
Pabis S., 1982. Teoria konwekcyjnego suszenia produktov rolniczych (Theory of heat conduction drying of agricultural products). Warszawa, PWRiL: 229.
Ražnjevič J., 1969. Tepelné tabuľky a diagramy (Thermal Tables and Diagrams). Bratislava, ALFA: 340.
SPP Bratislava, 2010. Zloženie zemného plynu 2009 (Composition of natural gas 2009). Available at www.spp.sk (accessed March 10, 2010).
Valchař J., Choc M., Tuma V., Kolář S., 1967. Základy sušení (Theory of Drying). Prague, ČVUT/SNTL: 396.
Vitázek I., 2006. Tepelné procesy v plynnom prostredí (Heat Processes in Gaseous Atmosphere). Nitra, SPU in Nitra: 98.
Vitázek I., 2008. Teplotechnika a hydrotechnika (Thermotechnics and Hydrotechnics). Nitra, SPU in Nitra: 104.
Vitázek I., Havelka J., 2010. Thermodynamics of combustion of fuel gases. In: ES 2010 Power System Engineering, Thermodynamics & Fluid flow. University of West Bohemia, Plzeň: 6.

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