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Harmonic pulse testing for gas well deliverability assessment*

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Harmonic Pulse Testing was introduced in the early 1970's as a special case of pulse testing. It is characterized by a periodic variation of production/injection rate. Subsequent developments proved that it could provide the same information as a conventional well test (permeability and skin, heterogeneity) in addition to those given by a pulse test (areal connectivity within the reservoir) if proper interpretation models were adopted. Consequently, it can be considered as a promising methodology to test a well during ongoing field operations without stopping production and thus it is very attractive for monitoring well performance, especially of gas storage wells.

Initially applied to oil wells, Harmonic Pulse Testing has recently been extended to gas wells for which the assumption of Darcy flow regime is no longer valid because of inertial phenomena and/or turbulence. Harmonic Pulse Testing for gas wells comprises three or more consecutive sequences of pulses characterized by increasing average rate, similar to a Flow After Flow test. The interpretation of a single-well Harmonic Pulse test is based on the derivative approach in the frequency domain to obtain kh and the skin components (mechanical skin and D factor). The possibility of assessing well deliverability from a multi-sequence pulse test was analysed in the research work presented in this paper. Different Pulse test configurations were considered and compared with the well-established Flow After Flow test in terms of deliverability estimate. To this end synthetic well test data were generated and sensitivity to test design, well parameters and reservoir interference were carried out.

Results show that multi-sequence pulse tests can be used to obtain the well deliverability of a gas well with the advantage that both the tested well and the neighboring wells needn't be shut-in prior to or during the test.

***Keywords**: unconventional well test, Harmonic Pulse Test, gas storage, gas well deliverabilities.*

Stima della capacità produttiva di pozzi a gas attraverso harmonic pulse test.
L'Harmonic Pulse Test (HPT) è stato introdotto nei primi anni '70 come un caso particolare di prova di pozzo di tipo Pulse Test, caratterizzato da una variazione periodica della portata di produzione/iniezione. Sviluppi successivi hanno dimostrato che, se vengono adottati i corretti modelli di interpretazione, una prova HPT è in grado di fornire le stesse informazioni di una prova di pozzo convenzionale (permeabilità, skin, eterogeneità) in aggiunta a quelle fornite da un Pulse Test (connettività spaziale all'interno del giacimento). Di conseguenza l'HPT può essere considerata una interessante metodologia di well test in quanto consente di testare il pozzo durante le normali operazioni di campo. Infatti, poiché non richiede l'interruzione della produzione, risulta particolarmente adatta per il monitoraggio delle prestazioni di pozzo, in particolare dei pozzi di stoccaggio a gas.

Inizialmente applicato ai pozzi ad olio, l'Harmonic Pulse Test è stato recentemente esteso a pozzi a gas per i quali l'assunzione di regime di flusso di tipo Darcy non è più valida a causa di fenomeni inerziali e/o di turbolenza. L'Harmonic Pulse Test per i pozzi a gas comprende tre o più sequenze consecutive di oscillazioni caratterizzate da una portata media crescente, in analogia ad un test di tipo Flow After Flow. L'interpretazione di un Harmonic Pulse Test a singolo pozzo per l'ottenimento di kh e delle componenti di skin (skin meccanico e fattore di turbolenza D) adotta l'approccio convenzionale della derivata opportunamente mutuato nel dominio di frequenza.

Il presente lavoro di ricerca analizza la possibilità di valutare la capacità produttiva di un pozzo a gas attraverso una prova di pozzo di tipo Harmonic Pulse Test multi-sequenza. Diverse configurazioni di Harmonic Pulse Test sono state considerate e confrontate con il consolidato test di tipo Flow After Flow in termini di stima di capacità produttiva. A tal fine sono stati generati dati di prova sintetici e sono state effettuate analisi di sensitività ai parametri di progettazione del test, ai parametri di pozzo e agli effetti di interferenza del giacimento.

I risultati mostrano che l'Harmonic Pulse Test multi-sequenza può essere utilizzato per la stima della capacità produttiva di un pozzo a gas senza richiedere la chiusura preliminare né del pozzo testato né dei pozzi circostanti.

***Parole chiave**: prova di pozzo non convenzionale, Harmonic Pulse Test, stoccaggio di gas, capacità produttiva dei pozzi a gas.*

1. Introduction

Harmonic Pulse Testing (HPT) has been developed as a special case of Pulse testing to determine well and near wellbore properties such as well productivity, formation damage, reservoir permeability and heterogeneities (Kuo 1972; Black and Kipp, 1981; Rosa and Horne, 1997; Hollaender *et al.*, 2002; Renner and Messar, 2006; Copty and Findikakis, 2004; Rochon *et al.*, 2008; Ahn and Horne, 2010; Fokker and Verga, 2011; Fokker *et al.*, 2012; Fokker *et al.* 2013; Vinci *et al.*, 2015; Sun *et al.*, 2015). An Harmonic Pulse test consists in imposing a periodic sequence of alternating rates and can be applied during ongoing production or injection operations, as a pulsed signal superimposed on the background signal. The main advantage of this testing approach is that it does not require the interruption of production nor the knowledge of previous rate history (Hollaender et al, 2002). In fact, the analysis in the frequency domain allows to extract and analyze each periodic component of the pressure response in relation to the corresponding periodic component of the rate. Harmonic Pulse Testing takes much longer than conventional well test to obtain the same information (Hollaender *et al.*, 2002); however it allows to monitor well performance without disrupting field operations. For this reason, application of HPT is particularly interesting in underground gas storage contexts or in reservoirs under production.

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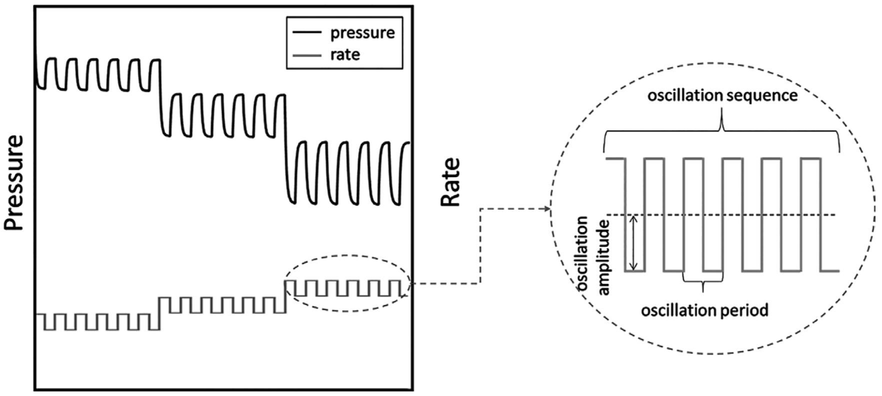

Fig. 1. Harmonic Pulse Test Scheme.
Schema di un Harmonic Pulse Test.

Initially applied to oil wells, the concept of single well harmonic pulse test has recently been extended to gas wells by proposing a sort of pulsing Flow After Flow (FAF) test (Salina Borello et al, 2016). The test is made up of three or more pulse sequences (Fig. 1), characterized by increasing average rates, in analogy to Flow After Flow test (Fig. 2). An equilibration period can be introduced between two adjacent pulse sequences.

A FAF, is a standard test for assessing Inflow Performance Relationship (Rawlins & Schellhardt, 1935). Because of the FAF multiple rate structure, interpretation of the test provides reliable gas well deliverability taking into account non-Darcy effects.

In the current paper, a throughout analysis of results provided by simulation of pulsing FAF test for several configuration is presented in order to investigate the reliability of the methodology in estimating gas well deliverability parameters.

2. Methodology

Similarly to a conventional FAF test interpretation, gas deliverability can be assessed through pulsing FAF interpretation by following either the empirical Back-pressure Equation (eq. 1) established by Rawlins and Schellhardt (1935) or alternatively the analytical relation derived by Houpeurt (1959). The Rawlins and Schellhardt (1935) approach is based on the empirical equation:

$$Q_g = C\left(p_s^2 - p_{wf}^2\right)^n \qquad (1)$$

where exponent n accounts for turbulence i.e. additional pressure drop due to high velocity of gas and performance coefficient C accounts for fluid properties, reservoir rock properties and reservoir flow geometry; it depends on permeability, area, Dietz shape factor, skin, flowing time and pressure dependent functions like viscosity and gas deviation factor.

The Houpeurt (1959) approach was obtained from a generalized radial diffusivity equation and is also called Laminar Inertial Turbulent method (LIT):

$$\frac{m(p_s)-m(p_{wf})}{Q_g} = A + BQ_g \qquad (2)$$

where m(p) is the pseudo pressure function, A is the coefficient of the laminar component, defined by eq. 3, and B is the coefficient of the Inertial Turbulent component, defined by eq. 4 (Ahmed, 2010).

$$A = \frac{T_R}{\pi k h}\frac{p_{sc}}{T_{sc}}\left(\ln\frac{r_d}{r_w} - \frac{3}{4} + S\right) \qquad (3)$$

$$B = \frac{T_R}{\pi k h}\frac{p_{sc}}{T_{sc}} D \qquad (4)$$

Similarly to FAF testing, C and n, or equivalently A and B, are identified thought a proper graphical representation of the pulsing FAF test data, as reported in Figure 3a and Figure 3b, respectively. However, in the case of FAF testing the graph is obtained by plotting the difference, in terms of pressure squared (or alternatively pseudo-pressure divided by rate), between the reservoir pressure and the pressure at the end of each flow period vs the corresponding rate (Fig. 4). Conversely, in the case of a pulsing FAF test each constant production step is replaced by an oscillating sequence, eventually followed by an equilibration time; thus, more choices are possible.

In this paper the impact of test configuration (i.e. presence and duration of equilibration period between pulsing sequences, number of pulses) on the gas well deli-

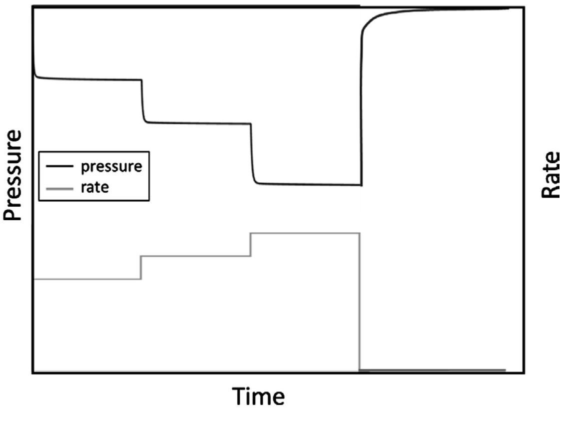

Fig. 2. Flow After Flow Test scheme.
Schema di un Flow After Flow Test.

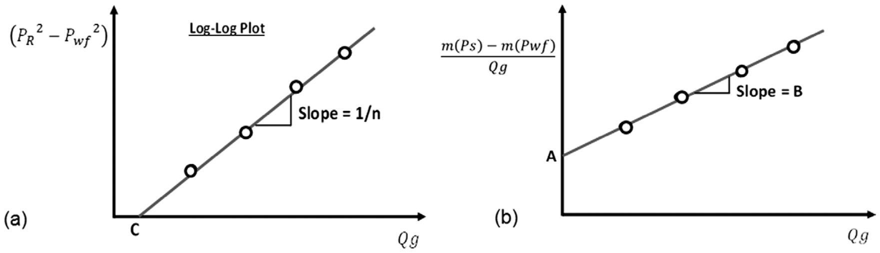

Fig. 3. (a) Rawlins & Schellhardt Method for finding C & n; (b) Pseudo-Pressure Quadratic Approach for finding A and B.
(a) metodo di Rawlins & Schellhardt per la stima dei parametri C ed n; (b) approccio quadratico in pseudopressione per la stima dei parametri A e B.

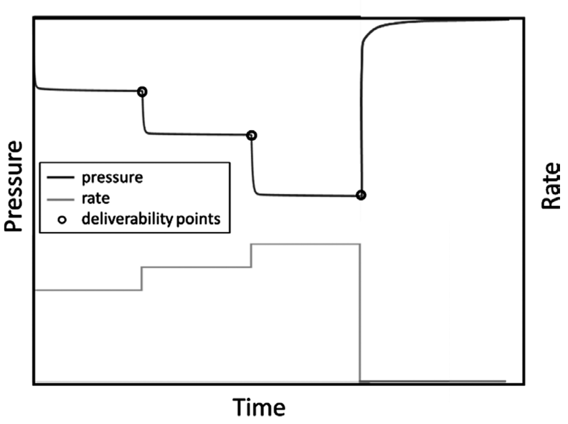

Fig. 4. Pressure and rate values selections for deliverability estimation in a FAF Test.
Selezione dei valori di pressione e portata per la stima della capacità produttiva da FAF Test.

verability estimation was assessed. To this end, test configuration with and without equilibration period were simulated and compared; for the configuration without equilibration period, two criteria for pressure and rate data selection were alternatively adopted. The main scenarios and the associated criteria are summarized as follows:

HPT1: Test with equilibration period at the end of the pulse sequence:

A. pressure point taken at the end of the equilibration period following the pulse sequence (Fig. 5a); average rate of the pulsing sequence as the corresponding reference rate

HPT2: Test without equilibration period:

B. pressure point taken at the end of the pulse sequence (no equilibration period) (Fig. 5b); average rate of the pulsing sequence as the corresponding reference rate
C. pressure point taken at the end of the pulse sequence (no equilibration period) (Fig. 5c); rate at the end of the sequence as the corresponding reference rate.

Moreover, the impact of interference with the pressure disturbance induced by ongoing operations in neighboring wells was assessed.

3. Validation scenarios

To evaluate the reliability of gas well deliverability parameters obtained by the Rawlins & Schellhardt Method and the LIT method from a pulsing FAF obtained via a FAF and HPT combination, a thorough comparison among results provided by conventional FAF testing and pulsing FAF was assessed. Different scenarios were simulated: initially no interference effects were considered; subsequently, interference was introduced imposing several production histories to an additional well in the neighborhood of the pulsing well.

3.1. Well & Reservoir data

A simple geometry synthetic gas reservoir intercepted by a vertical well was adopted for the sensitivity analysis. The reservoir model is 10000 m in both x and y directions with the well located into the center of the model in order to minimize the boundary effects. Main reservoir and well properties necessary for our purposes are summarized in Tab. 1. An additional

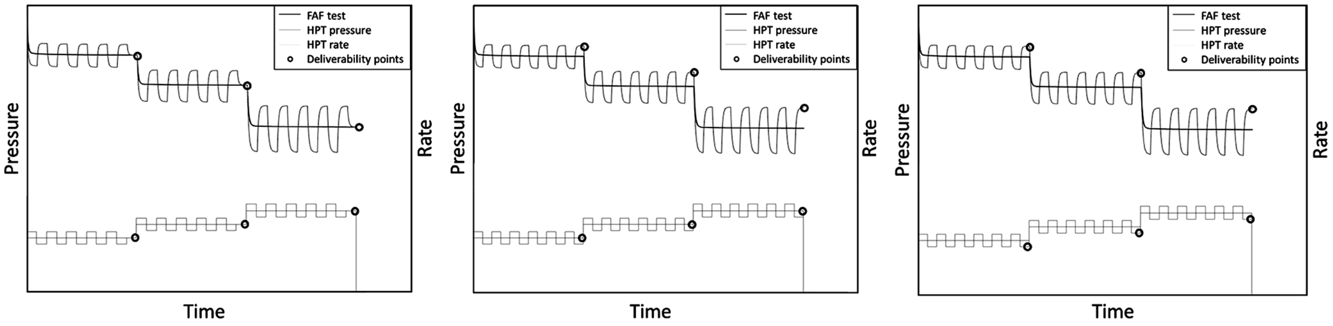

Fig. 5. Pressure and rate values selections for deliverability estimation.
Differenti criteri di selezione dei valori di pressione e portata per la stima della capacità produttiva da HPT.

Tab. 1. Well & Reservoir Description.
Dati di pozzo e giacimento.

Well	Well Radius	0.089	m
	Wellbore storage	2.168	bbl/psi
	Mechanical Skin	0	-
Reservoir	Pay zone	35	m
	Porosity	0.13	-
	Permeability	100	mD
	Total Compressibility	6.87E-3	bar^{-1}
	Temperature	47	°C
	Initial Pressure (p_i)	140	barsa
Gas	Specific gravity	0.613	-
	Viscosity @ p_i	0.016	cP
	Formation Volume factor @ p_i	0.0067	m^3/stm^3

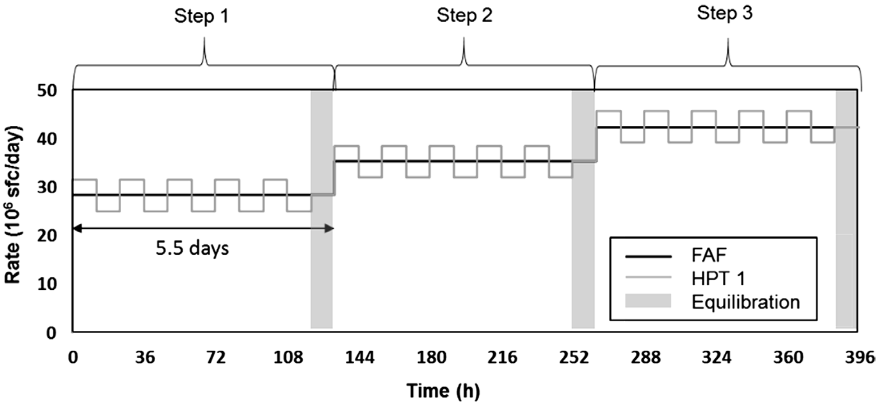

Fig. 6. Scenario HPT 1 vs. FAF test.
Confronto tra lo scenario HPT 1 ed il FAF test.

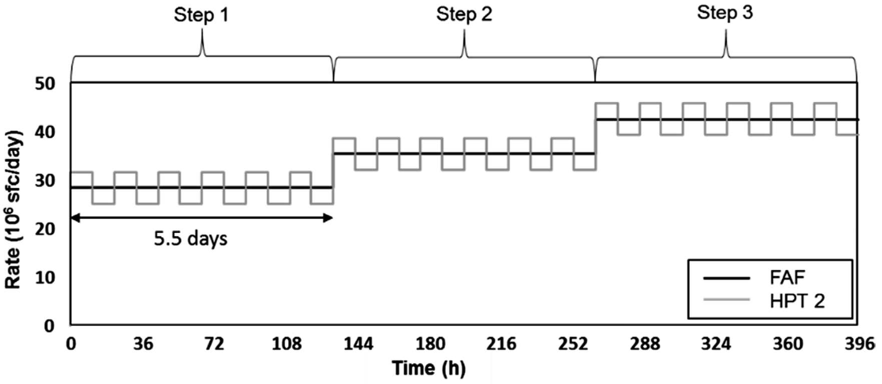

Fig. 7. Scenario HPT 2 vs. FAF test.
Confronto tra lo scenario HPT 2 ed il FAF test.

skin component Dq (Wattenbarger & Ramey, 1968) was introduced to account for different turbulence scenarios: from laminar flow (D = 0) to strongly turbulent flow (D = 1.5 10^{-3} $(10^3 scf/day)^{-1}$).

3.2. Test design

Pulsing FAF testing (FAF HPT testing) was designed with two different test configurations (tab. 2), both characterized by 5.5 days of overall duration (oscillation sequence + equilibration period) of each production step:

- HPT 1: equilibration period of 12h after each pulse sequence, at the average rate of the sequence (Fig. 6)
- HPT 2: no equilibration period between pulse sequences (Fig. 7)

The three approaches to the deliverability calculation described in the Methodology section were considered.

Conventional FAF testing, of which results serve as reference, was characterized by a rate history summarized in Tab. 3. It should be pointed out that the duration of each flow period of the FAF test corresponds to the duration of each production step (pulse sequence + equilibration period) of the HPT. The considered flow period duration is extremely long if compared to conventional FAF testing, however, said duration was dictated by a fair comparison.

Tab. 2. HPT Test History.
Storia produttiva degli HPT.

Test	Deliverability criterion	Step	Number of oscillations	Oscillation period (h)	Rate min (106scf/day)	Rate max (106scf/day)	Equilibration period (h)
HPT1	A	1	5	24	25	31.512	12
		2	5	24	32.064	38.576	12
		3	5	24	39.128	45.640	12
HPT2	B, C	1	6	22	25	31.512	0
		2	6	22	32.064	38.576	0
		3	6	22	39.128	45.640	0

Tab. 3. FAF Test History.
Storia produttiva del FAF test di riferimento.

Test	Step	Duration (days)	Rate (106scf/day)
FAF	1	5.5	28.256
	2	5.5	35.320
	3	5.5	42.384

3.3. Interference

In order to evaluate the effects of the interference on the results provided by both conventional and pulsing FAF tests further simulations were run adopting an interference well (Well 1) at a di-

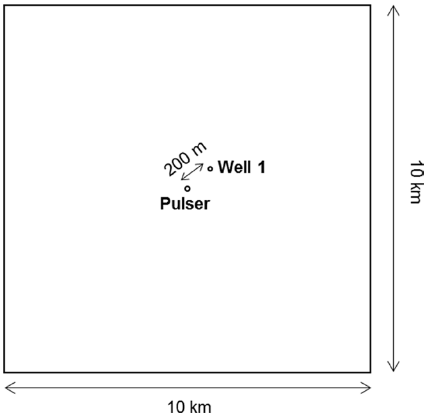

Fig. 8. Reservoir geometry and wells location for simulation of interference.
Geometria di giacimento e posizionamento dei pozzi per la simulazione degli scenari di interferenza.

Tab. 4. Interference rate scenarios.
Portate degli scenari di interferenza.

Scenarios	Interference type	Rate of Well 1 (106scf/day)	Rate after change (106scf/day)
Case 1	No interference	0	-
Case 2	Constant rate	50	-
Case 3	Rate change 100h before beginning of test	50	100
Case 4	Rate change at beginning of test	50	100
Case 5	Rate change 238 h after beginning of test	50	100

stance of 200 m from Pulser well (Fig. 8). Production in Well 1 started 60 days prior to the beginning of the test. Several rate histories of Well 1 were considered, as summarized in Tab. 4 and shown in Figure 9 and Figure 10. According to rock and reservoir fluids properties the pressure sink generated by Well 1 reaches the Pulser Well in 50 min approximately.

The pressure value at the beginning of the test was assumed to be an approximation of the static reservoir pressure for deliverability calculations.

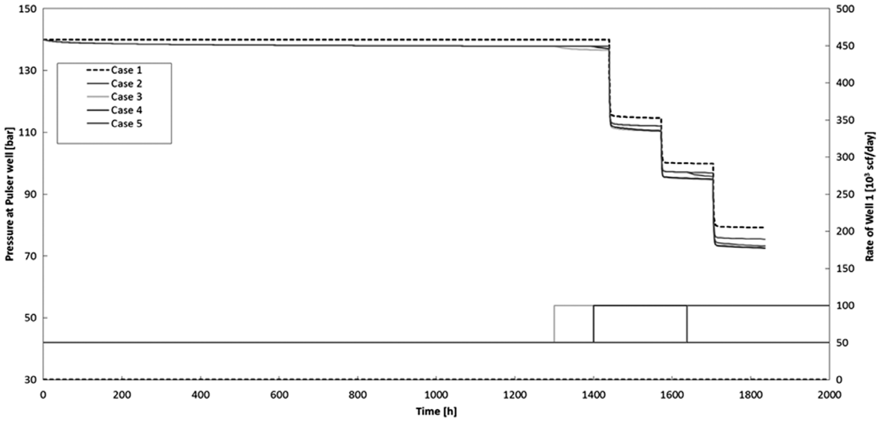

Fig. 9. Effect of Well 1 on pressure simulated for the tested well during the FAF.
Effetto del pozzo interferente Well1 sulla pressione simulata al pozzo testato con FAF test.

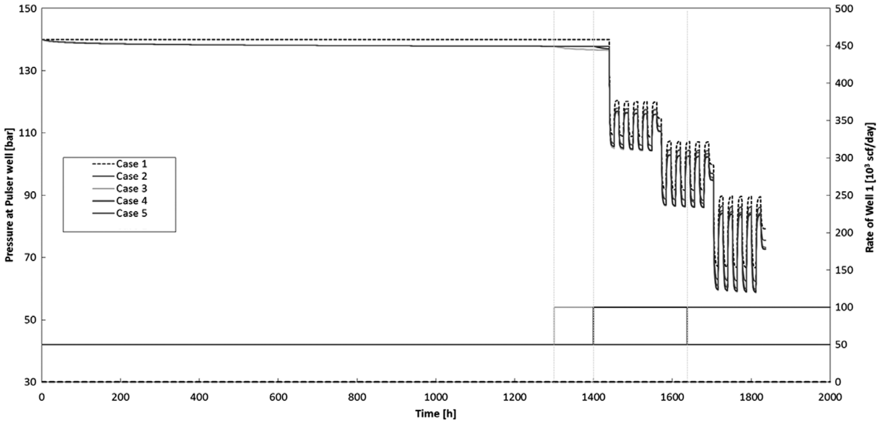

Fig. 10. Effect of Well 1 on pressure simulated for the Pulser during the pulsing FAF.
Effetto del pozzo interferente Well1 sulla pressione simulata al pozzo Pulser testato con pulsing FAF test.

4. Results and discussion

4.1. Results for no interference scenarios

Preliminary analyses were performed without interference effects and adopting different values of the non-Darcy coefficient D adopted in the numerical simulation. Gas Well deliverability coefficients C & n and A & B obtained from the interpretation of the simulated FAF and pulsing FAF tests were compared and represented as a function of the imposed non-Darcy coefficient D.

Results of scenario HPT1 are in good agreement with FAF test for all the coefficients (Fig. 11, Fig. 12).

Conversely, deliverability parameters obtained from HPT2 interpretation adopting criterion B were not representative and therefore the criterion was discarded during the preliminary analyses. Results of HPT2 with criterion C are in agreement with the FAF test limited to turbulence component coefficients n (Fig. 11b) and B (Fig. 12b). In all cases, the quality of the results are not affected by turbulence magnitude.

Additional sensitivities were performed for scenario HPT1 with the aim of evaluating the impact of the equilibration period (Δt_e) duration on the estimation of the gas well

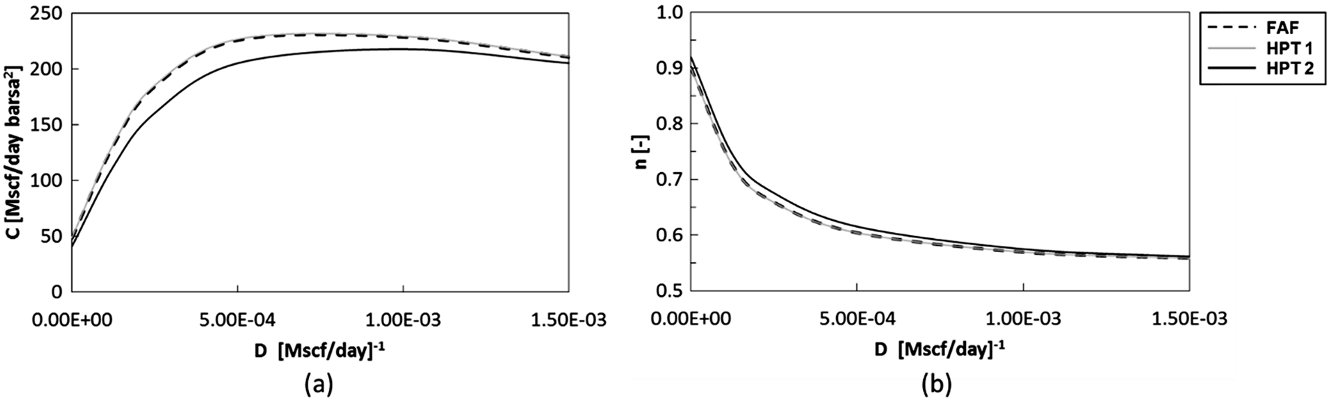

Fig. 11. Comparison of HPT configurations (solid lines) and FAF test (dotted line) in terms of estimated (a) C and (b) n.
Confronto tra le diverse configurazioni di HPT considerate (linee continue) ed il FAF test (linea tratteggiata) in termini di stima dei parametri (a) C e (b) n.

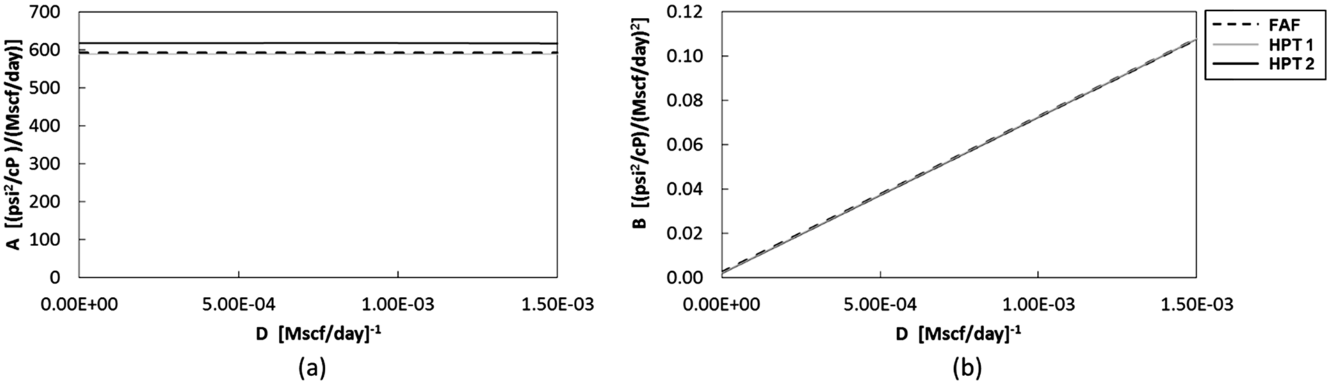

Fig. 12. Comparison of HPT configurations (solid lines) and FAF test (dotted line) in terms of estimated (a) non-turbulent and (b) turbulent component coefficients.
Confronto tra le diverse configurazioni di HPT considerate (linee continue) ed il FAF test (linea tratteggiata) in termini di stima dei coefficienti di componente (a) non-turbolenta e (b) turbolenta.

deliverability parameters. Results show that for short equilibration periods the estimation of coefficient A is not reliable, especially for high values of the non-Darcy coefficient (Fig. 13). However, for $\Delta t_e \geq T/3$ the estimate is acceptable.

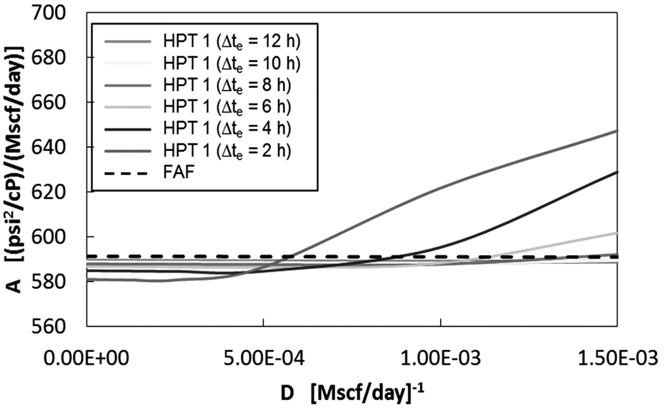

Fig. 13. Sensitivity to duration of the equilibration period (Δt_e).
Sensitività alla durata del periodo di equilibratura (Δt_e).

4.2. Results for scenarios characterized by interference

Interference phenomena have an impact on the gas well deliverability estimation for both conventional and pulsing FAF tests. Sensitivity analyses were performed assuming different production scenarios for Well 1 as summarized in Tab. 4. Results of the analysis are summarized in Figure 14 in terms of gas well deliverability parameters as a function of the imposed non-Darcy coefficient. If the production rate of Well 1 is kept constant during the FAF (or pulsing FAF test) and if rate changes at Well 1 occur at a much earlier time than the test start time (t_0) (Case 2 and Case 3 of Tab. 4), no impact on the evaluation of the gas well deliverability is detected; the results are in good agreement with the no interference scenarios (Case 1). On the other hand, Case 4 and Case 5 show a significant alteration of the estimated parameters due to the effect of interference.

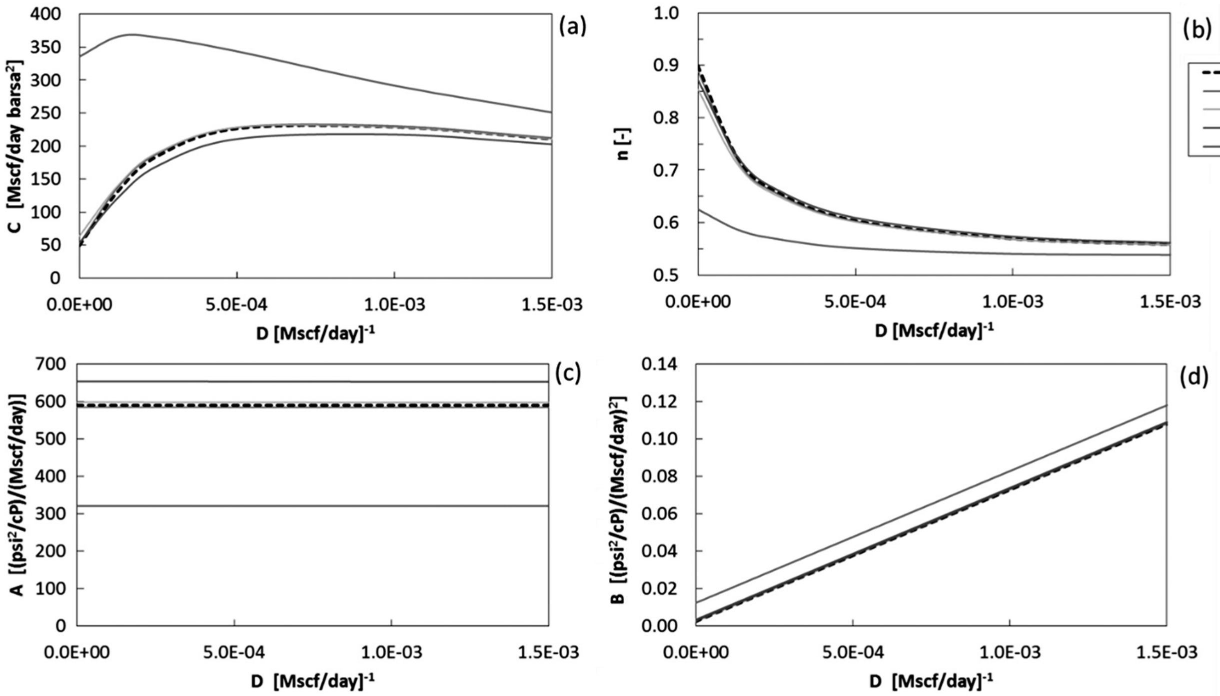

Fig. 14. Comparison of HPT in different interference scenarios (tab. 4) in terms of (a) C, (b) n, (c) A, and (d) B.
Confronto tra HPT in differenti scenari (tab. 4) in termini di stima dei coefficienti (a) C, (b) n, (c) A e (d) B.

5. Conclusions

Harmonic Pulse Testing (HPT) is a well test methodology aimed at the characterization of well and reservoir properties that does not require the interruption of production nor the knowledge of previous rate history. Interpretation in the frequency domain of the HPT rate and pressure data provides the estimation of parameters such as permeability of the formation and skin. Field trend and non-periodic interferences are not a concern in the frequency analysis approach.

Gas wells are affected by turbulence phenomena. Therefore, estimation of gas well deliverabilities requires performing a multirate test, typically a FAF test, that provides suitable data for characterizing the linearly rate-dependent non-Darcy behavior of the bottom hole pressure.

A combined HPT and FAF test, named pulsing FAF test, was investigated through numerical simulation of several scenarios and subsequent interpretation for gas well deliverability characterization adopting well established methodologies, i.e.: Rawlins & Schellhardt and LIT methods.

A number of simulations were run for a parametrical analysis on turbulence effects, through different values of non-Darcy coefficient, and interference phenomena. Results were compared with those provided by a conventional FAF test under the ideal condition of no interference with other wells.

Analysis of results demonstrated that gas well deliverability parameters obtained from pulsing FAF test, are in good agreement with those obtained from a conventional FAF test in ideal conditions, but three main requirements must yet be met:

- Multirate HPT is performed, i.e. HPT made up of at least three sequences of oscillations with increasing average rate.
- Each oscillating sequence is followed by an equilibration period of duration $\Delta t_e \geq T/3$ in which gas is produced with a constant rate equal to the average sequence rate.
- Neighboring wells are produced with constant rate during the entire test and if possible for a while before the beginning of the test.

It should be pointed out that constant rate production from neighboring wells is a requirement that can be easily respected when all the wells of a field are producing, but could be more critical during a gas injection period associated with storage operations. Furthermore, being pulsing FAF test duration significantly longer than that of a conventional FAF test, it should be considered as an alternative only when stopping production is not an option.

6. Nomenclature

A Laminar Flow Coefficient
B Inertial Turbulent Flow Coefficient
C Rawlins & Schellhardt Performance Coefficient
D Non-Darcy Flow Coefficient
h Net Pay Thickness

k	Reservoir Average Permeability
$m(p_s)$	Pseudo Static Pressure
$m(p_{wf})$	Pseudo Bottomhole Well Flowing Pressure
n	Rawlins & Schellhardt exponent
p_R	Average Reservoir Pressure
p_{sc}	Standard Condition Pressure
Q_g	Gas Flow Rate
r_d	Drainage Radius
r_w	Well Radius
S	Mechanical Skin
T_R	Reservoir Temperature
T_{sc}	Standard Condition Temperature

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